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UNIVERSITY OF ALBERTA

# Rock slope movements in Kananaskis Country

by

Xian-qin Hu

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Doctor of Philosophy

Department of Geology

EDMONTON, ALBERTA

Spring, 1991

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Date 22 April 1991

## Abstract

Rock slope movements in stratified rocks in Kananaskis Country, Alberta are controlled by topography, discontinuity orientations and their spacings and external forces. Different types of slope movements occur on different types of slopes. Both catastrophic and noncatastrophic slope movements modify landforms but in different ways.

Movements on anaclinal slopes are either topples followed by sliding or slides along discontinuities or combinations of discontinuities. When bedding surfaces dip at less than 50°, small rock masses can slide along strike joints or fall and slope angles remain unchanged. When bedding surfaces dip at about 65°, large rock masses topple and then slide or simply slide along sheeting joints or combinations of bedding surfaces and strike joints to reduce slope gradients.

On cataclinal underdip slopes, topples up to 15 metres thick develop in Mesozoic sandstones. Toppling style is controlled by discontinuity spacings. Block flexure topples occur where ratios of joint spacing to bedding thickness (h/b) are less than two. Complex, multiple block topples occur where h/b ratios are 2 to 20 and sliding surfaces develop in topples, either cut through thin bedding layers or follow a combination of discontinuities. Chevron topples develop when slope angles are over 35° in rock masses with the same h/b as those of complex multiple block topples. Sliding may occur along hinge surfaces of chevron topples.

Toppling reduces slope angles and stabilizes slopes.

Several steeply dipping layers can buckle together in styles controlled by bedding thickness. Thin beds form chevron buckles while thicker beds form Euler buckles in layers without cross fractures, block flexure buckles in layers with cross fractures or block buckles with large relative displacements of individual blocks. Further displacements of buckled layers can form roof and wall structures and cascades.

On orthoclinal and plagioclinal slopes, slope movements are started by sliding of rock blocks along intersections of bedding surfaces and strike joints or toppling from dip joints and followed by sliding along bedding surfaces.

A portable tilting table for measurement of friction angles is suitable for testing smooth surfaces of discontinuites in the field and as many samples as needed can be tested. The results from sandstone bedding surfaces are close to the basic friction angles.

Rock masses displaced in open rock basins are also controlled by geological structures. There are no rock basins on steep dip slopes but basins develop on overdip slopes. Rock basins develop on wide ranges of slope angles and bedding dips on anaclinal slopes and catastrophic movements can create rock basins on steepened anaclinal slopes. Basins occur on underdip slopes except on slightly underdip slopes. On orthoclinal and plagioclinal slopes, basins develop by sliding along intersections of bedding

planes and strike joints or toppling from dip joints in weak units.

**Acknowlegement**

The author would like to thank my supervisor, Dave Cruden. His consistent guidance and help were essential for the completion of the thesis.

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## LIST OF SYMBOLS

SYMBOLS IN FIGURES:

OD → Cataclinal overdip slopes

D → Cataclinal dip slopes

UD → Cataclinal underdip slopes

RD → Anaclinal slopes

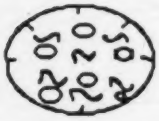
S → Orthoclinal slopes

O → Plagioclinal slopes

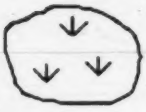
Displaced materials from slope movements such as rockslides or rockfalls.

Talus deposits on maps.

Talus deposits on figures for interpretations of field-taken plates.



Deposits from rock glacier



Vegetation

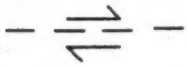
Creeks or gullies on maps

Geological boundaries

Unconfirmed geological boundaries

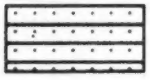
Thrust faults

Unconfirmed thrust faults



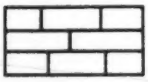
Unconfirmed tear faults on maps

Faults on cross sections

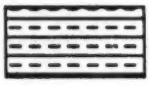


Sandstones

Dolostones

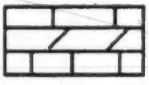


Limestones

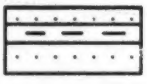


Shales

Calcareous sandstones



Interlayered limestones and dolostones



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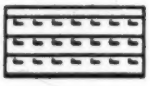
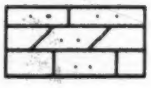


Quartzites



Interlayered limestones and dolostones with cherts

Shaly dolostones

Sandy dolostones

SYMBOLS FOR GEOLOGICAL FORMATIONS (GROUPS):

| | |
|---|---|
| **Lower Cretaceous** | |
| Kbl | Blairmore Group |
| **Cretaceous and Jurassic** | |
| Jk | Kootenay Formation |
| **Jurassic** | |
| Jf | Fernie Group |
| **Triassic** | |
| Trs | Spray River Group |
| **Permo-Pennsylvanian** | |
| Prm | Rocky Mountain Group |
| **Mississippian** | |
| Mr | Rundle Group |
| Mth | Etherington Formation |
| Mh | Mount Head Formation |
| Ml | Livingstone Formation |
| Mb | Banff Formation |
| Me | Exshaw Formation |
| **Devonian** | |
| Dp | Palliser Formation |
| Df | Fairholme Group |

SYMBOLS IN EQUATIONS AND FOR ROCK BLOCK DESCRIPTIONS:

| | |
|---|---|
| $\beta$ | Bedding dips |
| $\gamma$ | Density of rock |
| $\sigma$ or $\sigma_n$ | Normal stress |
| $\sigma_c$ | Uniaxial compressive strength |
| $\tau$ | Shear stress |
| $\phi$ | Friction angle |
| $\phi_b$ | Basic friction angle |
| $\Psi$ | Slope angle |
| c | Cohesion |
| i | Roughness angle |
| H | Slab thickness for potential slides in vertical direction |
| SF | Factor of safety |
| b | Bedding thickness |
| h/b | Ratio of joint spacings to bedding thickness |

# 1. Introduction

## 1.1 Origin of the research

Slope movements and instabilities in stratified rocks have been subject of considerable interest in the Canadian Rockies. Most of the detailed work has been on sliding of rock masses along penetrative discontinuities (Eisbacher, 1971, Cruden and Krahn, 1973, Cruden, 1976, Locat and Cruden, 1977, Bruce and Cruden, 1980). Gardner (1978, 1980, 1983) discussed the frequency, magnitude and spatial distribution of rockfalls. Wyllie (1980) and Tang (1986) studied topples. Sliding over penetrative discontinuities which extend persistently over large areas, such as bedding planes or foliations, can be simulated by sliding blocks over inclined planes. Mechanisms and processes of sliding across penetrative discontinuities, buckling and toppling are not well understood and few cases have been described.

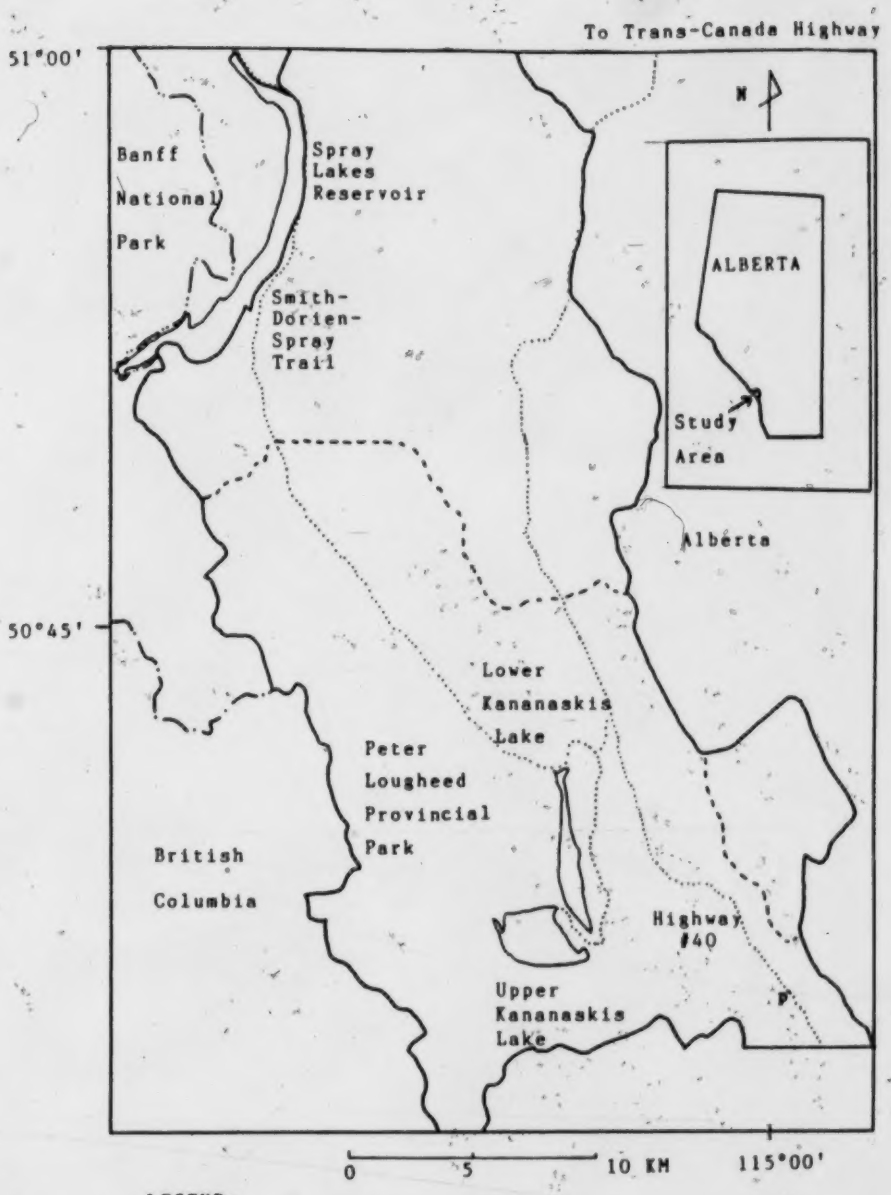
Since the retreat of the last glaciation, slope movements have occurred on many rock slopes in stratified rocks in the Canadian Rockies. These slope movements have created various landforms and produced a lot of displaced materials. The modes, processes and magnitudes of slope movements control landform evolution and are important in evaluations of slope stabilities. But little research has been systematically conducted into the geological control of slope movements and landform formation for different combinations of slope orientations and discontinuity

orientations in stratified rocks.

In order to better understand mechanisms and processes of slope movements other than sliding along penetrative discontinuities and to determine geological factors controlling these mechanisms and processes in stratified rocks, a field investigation was conducted in 1988 and 1989 in Kananaskis Country, west of Calgary, Alberta (Fig. 1.1) based on the work by Eaton (1986) and Hu (1987).

Eaton (1986) identified 228 deposits from different types of slope movements including rocksliding along and across penetrative discontinuities and rockfalling. All these slope movements developed in carbonates and clastics in Kananaskis Country. Tang (1986) described topples around the Highwood Pass. Both Eaton (1986) and Tang (1986) did not study individual slope movements in detail. Hu (1987) studied the stabilities of potential rockslides as a continuation of the research by Eaton (1986) in the same area. My investigation in 1988 and 1989 was conducted around the slope movements of Eaton (1986) and Tang (1986). Slope movements in the study area, lithologies and geological structures around these slope movements were mapped. A large number of slope movements were investigated in detail.

Sauchyn (1984) mapped the geometries of 56 open rock basins in Kananaskis Country using digital elevation models. Because these rock basins are influenced by rock mass movements, the landforms created by these slope movements should relate to the geological structure as well as




LEGEND:

Study area boundary: ——————
Peter Lougheed Provincial Park
boundary inside study area: — — — — —
Banff National Park boundary: —·—·—·—
Provincial boundary: ——·——·——
All weather road: ·····
P: Highwood Pass parking lot in Highway #40.

Figure 1.1 Study area

lithology of the basins. I investigated the geological structure, lithology and slope angles of 55 of Sauchyn's rock basins. A study of the relationship between landforms and slope movements based on my investigations on these basins and Sauchyn's geometrical data as well as the results of the research on slope movements in Kananaskis Country is conducted.

## 1.2 Slope classification and processes of slope movements

Cruden and Hu (1990) classified rock slopes in stratified rocks into several types according to the relationship between orientations of penetrative discontinuities and directions and dips of slopes. The slope types are orthoclinal slopes, plagioclinal slopes, anaclinal slopes and cataclinal slopes (Fig. 1.2). Cataclinal slopes can be further divided into underdip slopes, dip slopes and overdip slopes and anaclinal slopes can be divided into steepened, normal and subdued anaclinal slopes (Fig. 1.3). I call underdip slopes that are close to dip slopes slightly underdip slopes. Cruden and Hu (1990) also gave a process diagram which illustrated the relationship between certain slope movements and orientations of penetrative discontinuities and slopes assuming friction angles of 30° and cohesion of zero along discontinuities. Different types of slope movements are defined by different slope types on this process diagram (Fig 1.4). On this diagram, only rocksliding along penetrative discontinuities (e.g. Cruden,

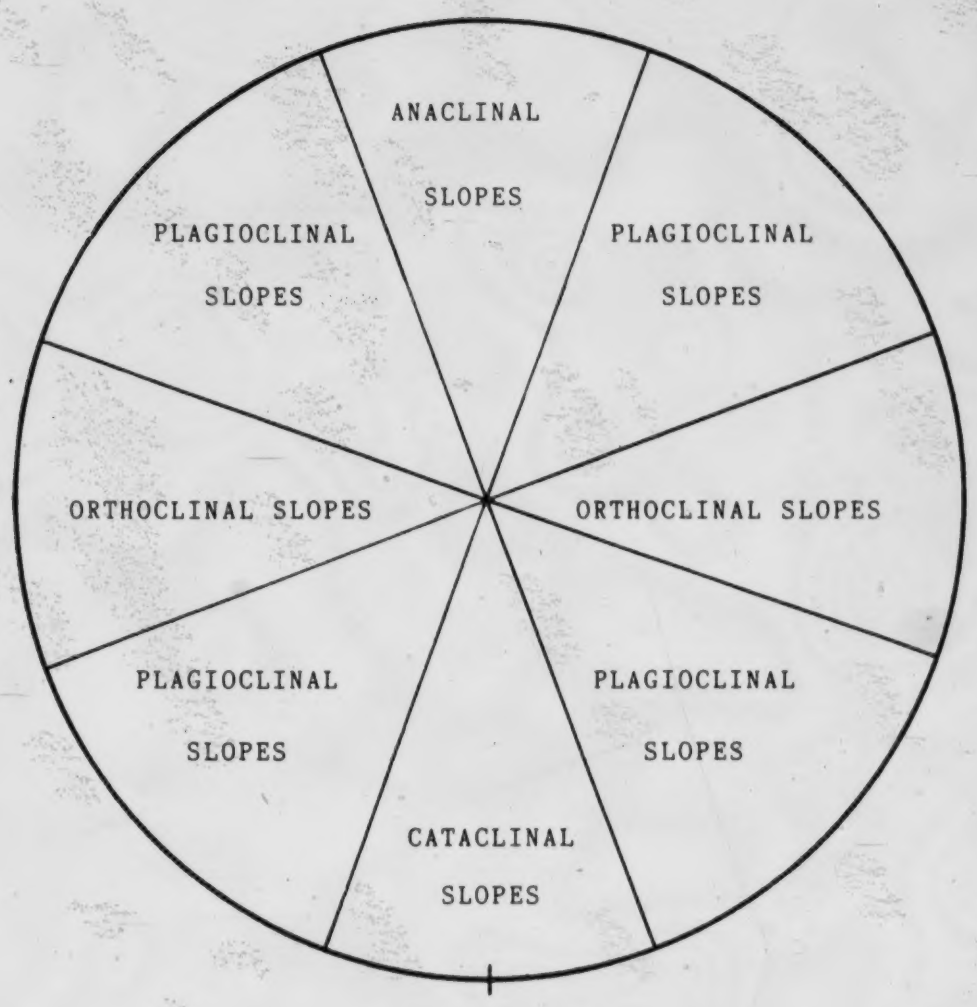



Figure 1.2 Slope classification in stratified rocks based on orientations of penetrative discontinuities and of slopes

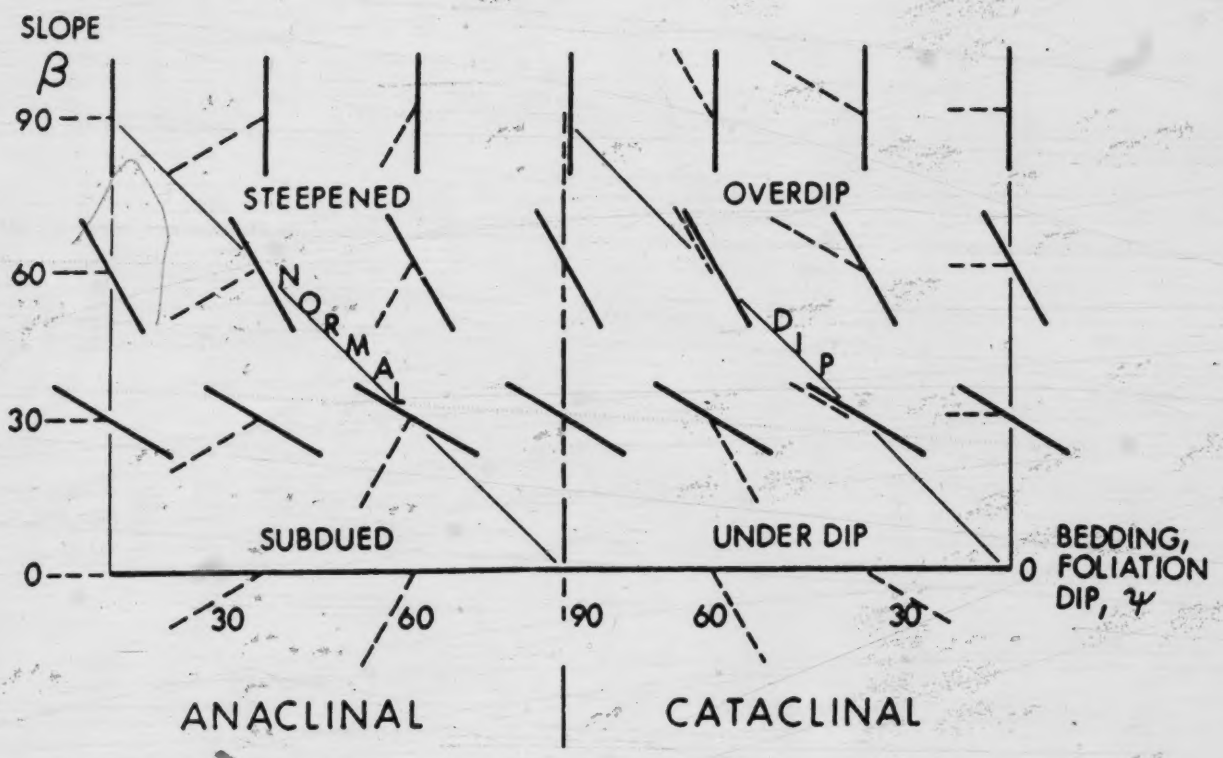
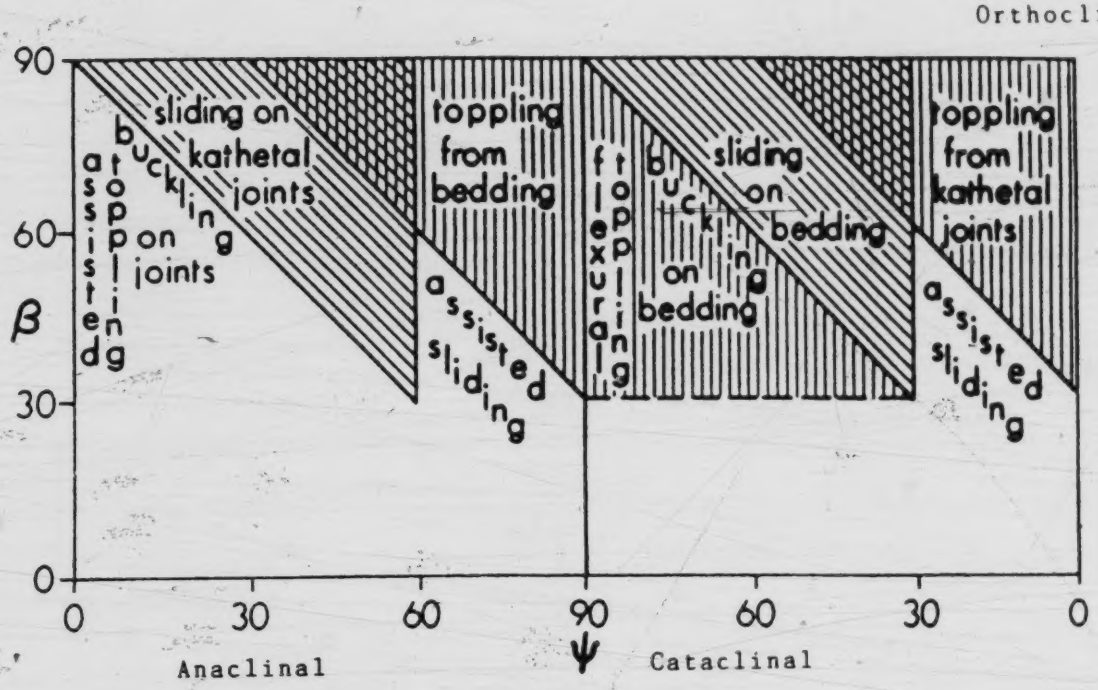



Figure 1.3 Slope classification for cataclinal slopes and anaclinal slopes based on dips of penetrative discontinuties and slope angles. Dashed lines and solid lines represent bedding and slopes respectively. Modified from Cruden (1987).




Kathetal joints are cross fractures.
Assisted sliding and assisted toppling are those movements assisted by external forces such as seismic forces.

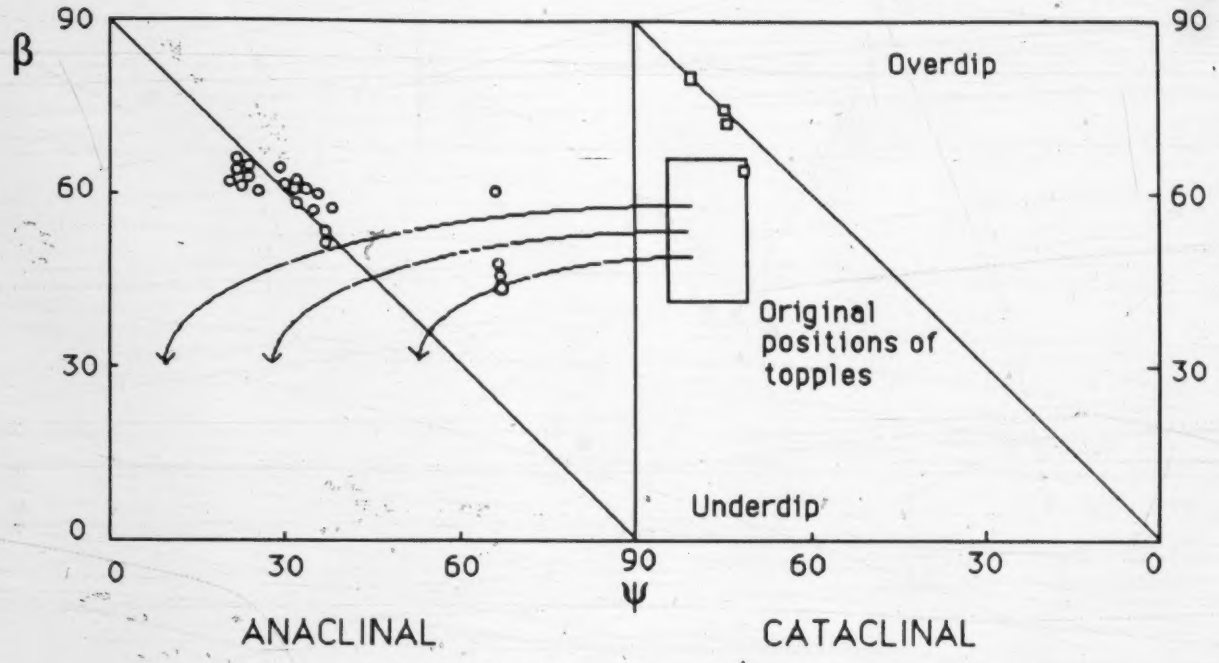
Figure 1.4 Process diagram of slope movements in stratified rocks. Friction angle and cohesion are assumed 30° and zero respectively. After Cruden and Hu (1990).

1985 and Eaton, 1986) and rocktoppling on anaclinal slopes (e.g. Goodman and Bray, 1976) have been closely studied. On anaclinal slopes, either toppling or sliding along cross joints may occur with the same orientations of discontinuities and slopes on the region for both toppling from bedding and sliding on kathetal joints. Geological factors determining types of slope movements on anaclinal slopes are not known. In the thesis, slope movements on anaclinal slopes, on cataclinal underdip slopes and on orthoclinal and plagioclinal slopes are studied.

### 1.3 Scope of the thesis

Rock masses on anaclinal slopes move along cross joints by falling or sliding or toppling of rock layers followed by sliding along some rupture surfaces. For the slope movements investigated, displaced masses of $0.1 \times 10^4$ m$^3$ to $6 \times 10^4$ m$^3$ are found below anaclinal rock slopes. Orientations of penetrative discontinuities vary between 25° and 70° dipping into slopes. Some slopes are normal escarpments and some are oblique to both penetrative discontinuities and cross fractures after movements of slopes (Fig. 1.5). These slope movements are discussed in Chapter 2.

Topples on anaclinal slopes have been studied by Goodman and Bray (1976) who classified topples on anaclinal slopes by their deformation mechanisms. Cruden (1989) showed that it is kinematically possible for topples on underdip slopes to occur with the same assumptions used by Goodman




ψ: Dips of penetrative discontinuities.

β: Slope angles.

o Current positions of slope movements on anaclinal slopes.

Topples and their changes of orientations.

▫ Buckles before failure or large downslope movements.

Figure 1.5 Schematic diagram showing relationship between orientations of penetrative discontinuities and slopes for some slope movements in Kananaskis Country

and Bray (1976). Topples on underdip slopes are developed on steeply dipping beds around the Highwood Pass, in the southern part of Kananaskis Country. The untoppled bedding layers are all at 70-90°/235-245°, represented as dip and dip direction. Layers are rotated to dip to the northeast at 0° to 70° for different topples (Fig. 1.5). Topples and further mass displacements are related to local geological conditions. In Chapter 3, the deformation styles of these topples, the structures formed during toppling processes and the geological controls of toppling and toppling processes are described and analyzed.

Cavers (1981) gave a few mechanisms of rock buckling but no buckles have been described or discussed on natural slopes in the Rockies. The buckles I have found in the Highwood Pass (Fig. 1.5) have more complicated mechanisms than those from Cavers (1981). Deformation of layers varies with geological structures, particularly bedding thickness. The buckles can involve more than one layer. Some of the buckled structures have moved downslope long distances after the layers buckled. In Chapter 4, a few examples of buckles in steeply dipping layers are described and then mechanisms and buckling processes are analyzed.

It is always important to determine friction angles of discontinuities in studies of rock slope movements. The basic friction angle of the rock is a useful estimate of the friction angle along a penetrative discontinuity in the Rockies (Cruden, 1985) and the basic friction angle can be

determined from rock surfaces lapped with #80 grit (Hu, 1987). In order to get quick estimates of friction angles of discontinuities in the field, a portable tilting table was made in the Department of Civil Engineering, University of Alberta. In the field, rock samples can be selected to find the minimum sliding angle of potential sliding surfaces and as many samples as wanted can be tested using the portable tilting table. In Chapter 5, the structure and use of the portable tilting table are discussed and some field measurements are given, which are compared with those tested in the laboratory.

Based on the geometrical data from the rock basins collected by Sauchyn (1984) and the structural data I collected in the summer of 1989, Sauchyn *et al.* (1990) concluded that sizes and shapes of the basins relate to the slope types of Cruden and Hu (1990) and that processes of landform formation are influenced by slope movements, which explained some aspects of the relationship between landform evolution and slope movements. Chapter 6 examines the relationship between slope movements and gradients of slopes on different types of slopes. Different types of slope movements are reviewed first and typical slope movements on orthoclinal and plagioclinal slopes are described because no such descriptions have been given. Then relationships between slope gradients and slope movements are evaluated based on the geometrical data both from Sauchyn (1984) and from my field investigations.

The conclusions are given in the final chapter.

The thesis is in paper format and each chapter has its own references.

Many figures used in the thesis are overlays based on photographs taken in the field. Scales for these overlays and photographs are estimated from objects in the centres of the photographs. Vertical scales and horizontal scales are assumed the same.

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# 2. Rock Mass Movements on Anaclinal Slopes in Kananaskis Country, Alberta

## 2.1 Introduction

All large rockslides described from the Rockies have slid down bedding planes (Cruden, 1985). When Eaton (1986) mapped rock slopes in Kananaskis Country, Alberta (Fig. 2.1) where some movements had taken place across bedding planes a more detailed investigation was called for. As a result, I identified 23 movements based on the work by Eaton (1986) and investigated them in the summers of 1988 and 1989. These slope movements on anaclinal slopes occur in the Palaeozoic carbonates and clastics and access to most of the slopes is easy.

Here I report the geological structures, lithology and characteristics of the displaced rock masses and rupture surfaces of these anaclinal slopes. I describe the first major slope movement on an anaclinal slope in the Canadian Rockies and study relationships among geological structures, lithologies and slope movements on anaclinal slopes using observations from the 23 slope movements.

The major slope movement, Elk Ridge slide, is in the region of toppling from bedding in the process diagram of Cruden (1987, Fig. 5). Sliding along the current slope may be also possible because the slope angle varies from 45° to 60° on the east slope of Elk Ridge where the slide took place. In order to evaluate the stability of the original slope with respect to toppling and sliding, back analyses

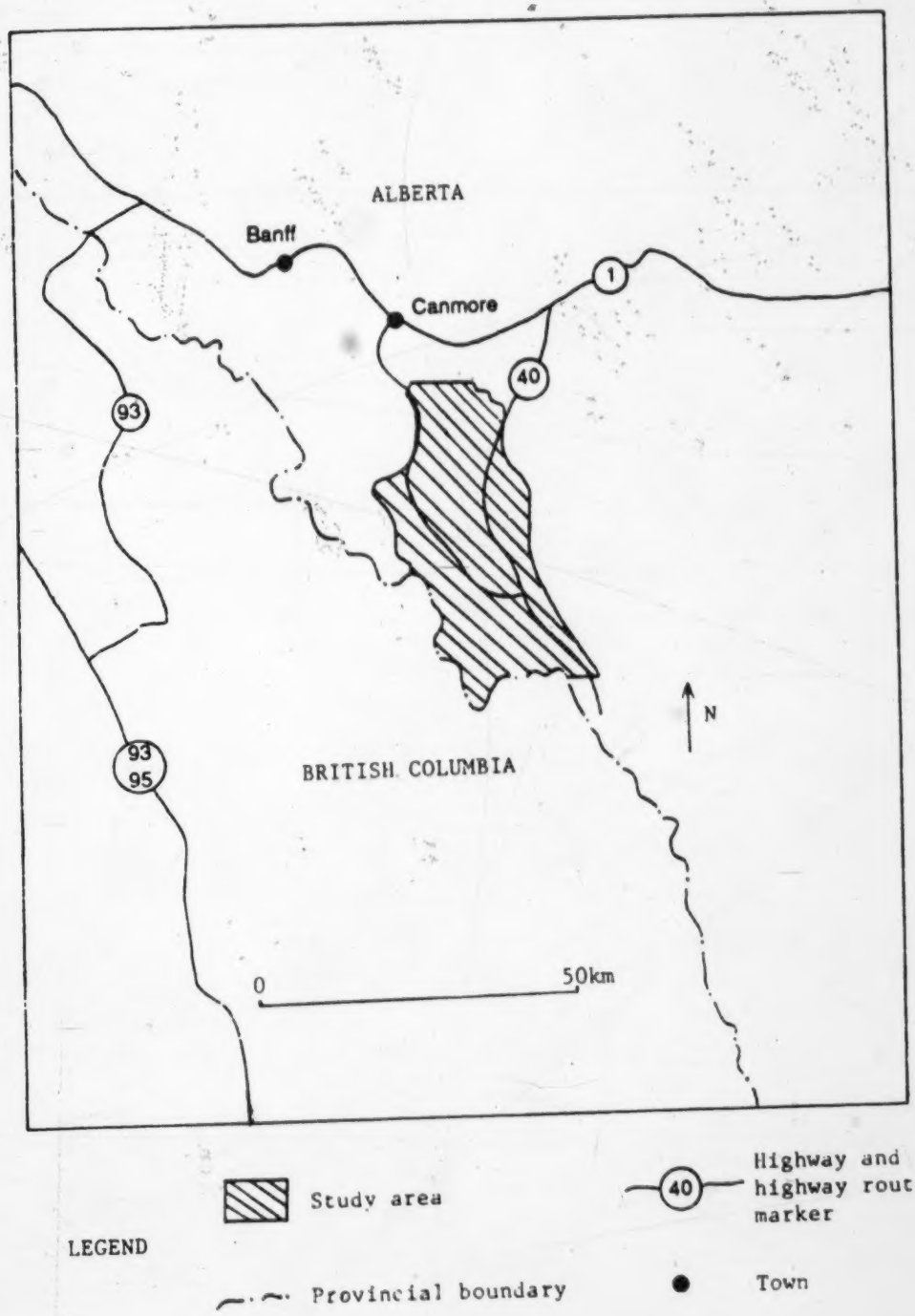



**Figure 2.1 Study area for slope movements on anaclinal slopes**

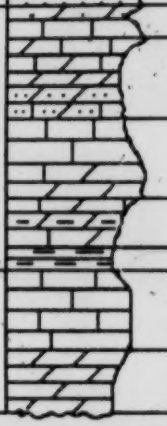
are conducted using the block toppling model (Goodman and Bray, 1976) and the sliding model along highly jointed rock masses (Hoek and Bray, 1977) in this chapter.

Rockfalls and rockslides are terms used to describe slope movements. Rockfalls are the free falls of newly detached blocks of bedrock down a steep slopes. Rockslides are movements of newly detached blocks of bedrock, sliding down the surfaces of discontinuities. These definitions of rockfalls and rockslides follows Varnes (1978). Rockfalls are commonly small and frequent but rockslides are large and infrequent.

## 2.2 Bedrock Geology

The study area is cut by a few thrust faults striking northwest-southeast (Bielenstein *et al.*, 1971). Strong old sedimentary rocks uplifted by thrust faults form mountain ranges and relatively weak and younger rocks floor the valleys. Rock slope movements on anaclinal slopes have occurred in the Devonian Fairholme Group, the Devonian Palliser Formation, the Mississippian Rundle Group which includes the Livingstone Formation, Mount Head Formation and the Etherington Formation and the Permo-Pennsylvanian Rocky Mountain Group (Fig. 2.2). Several anticlines and synclines extend parallel to the strike of the thrust faults (Bielenstein *et al.*, 1971).

The rocks contain at least two joint sets, both perpendicular to bedding surfaces. The strikes of the two

| PERIOD | LITHOLOGY | GROUP | FORMATION | SYMBOL | | REMARKS |
|---|---|---|---|---|---|---|
| Permian, Pennsylvanian | | Rocky Mountain* | | Prm | | |
| Mississippian |  | Rundle* | Etherington | Mr | Mth | 1 |
| | | | Mount Head* | | Mh | 2 |
| | | | Livingstone* | | Ml | 3 |
| | | | Banff* | Mb | | 4 |
| | | | Exshaw* | Me | | 5 |
| Devonian |  | | Palliser* | Dp | | 6 |
| | | Fairholme* | | Df | | 7 |

* Where slope movements develop on anaclinal slopes.

Remark 1, lithology is based on Douglas (1958, P.62).

Remark 2, lithology is based on Macqueen *et al.* (1972).

Remark 3, lithology is based on Douglas (1958, p.39).

Remark 4, lithology is based on Macqueen *et al.* (1972).

Remark 5, lithology is based on Macqueen *et al.* 1972).

Remark 6, lithology is based on Beach (1943).

Remark 7, lithology is based on Raymond (1930) and Ollerenshaw (1968).

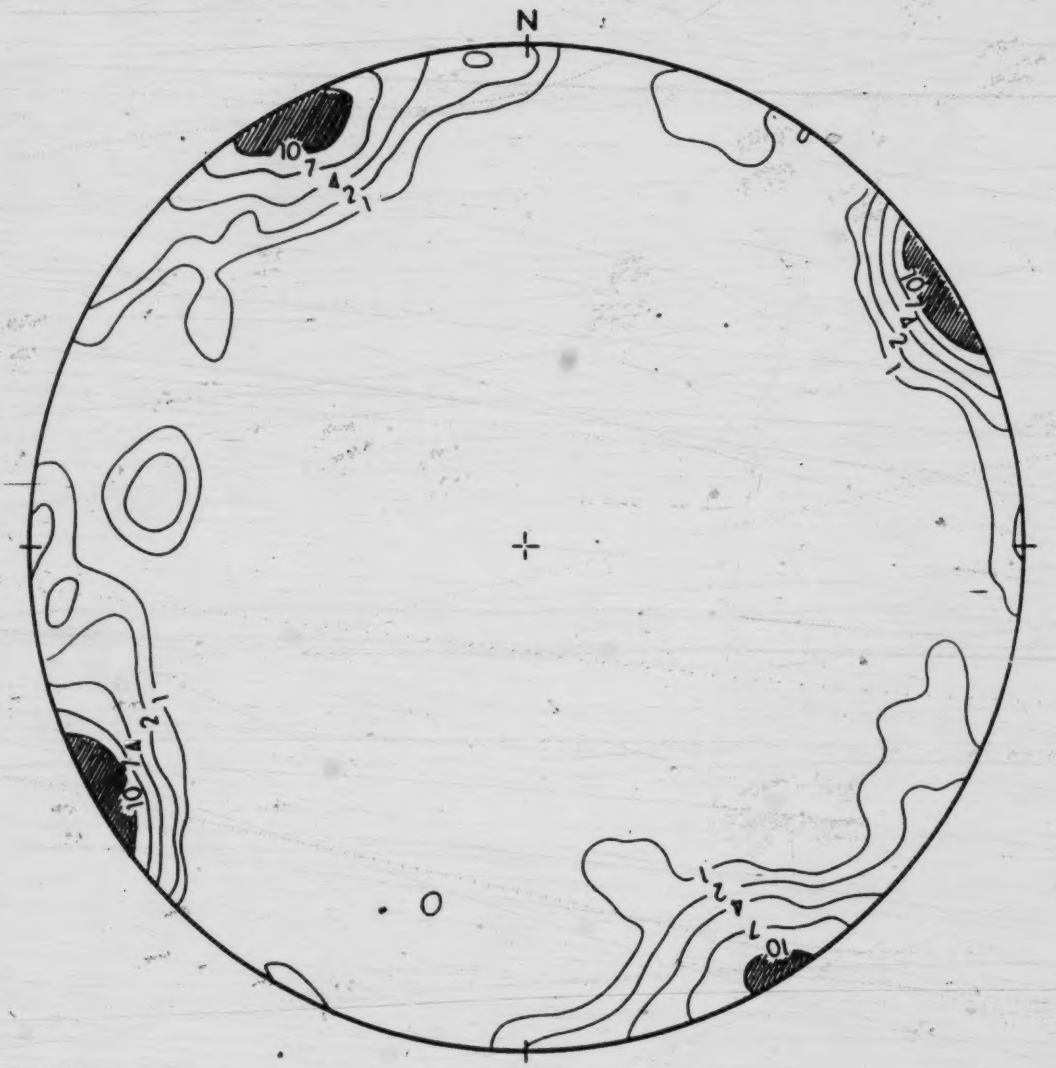
Figure 2.2 Stratigraphical column showing rocks encountered on slope movements on anaclinal slopes

joint sets are respectively perpendicular and parallel to the strike of the bedding (Fig. 2.3).

Sheeting joints have formed parallel to slope surfaces. They resemble those in granites (Terzhaghi, 1962) in the relationship between their orientations and topography. Their spacing is generally less than 3 metres although they may not closely parallel each other like tectonic joints. Sheeting joints have been found only in units with large discontinuity spacings, such as the Palliser Formation and the Livingstone Formation. Sheeting joints have only been found on anaclinal slopes, where the exposed trace lengths can reach 10 metres.

## 2.3 Slope movements on anaclinal slopes

On anaclinal slopes, the penetrative discontinuities like bedding planes dip into the slope and the angle between the strikes of the slope and of the penetrative discontinuities is less than 20° (Cruden, 1987). Anaclinal slopes are commonly referred to as escarpments when penetrative discontinuities dip gently into the slopes. Rock slides on anaclinal slopes have been described by Hutchinson (1969) who studied the slides occurring in the gently-dipping Middle and Lower Chalk at Folkestone warren, Kent, Britain and Eisbacher and Clague (1984) who described 23 rock avalanches in the Alps on anaclinal slopes in strong formations, commonly carbonates, overlying incompetent rocks. Eisbacher and Clague (1984, p.48) noted that




The probability diagram (K=100) is on an equal angle projection.

446 joints are included and the joints from all the units in Fig. 2.2. Sheeting joints are not included due to small number of measurements.

All the joints have been rotated by bedding dips about their strikes of beds which are all about 150°.

Figure 2.3 Polar diagram of joints from Kananaskis Country.

escarpments may be controlled by regional fracture sets trending parallel to major fold structures (tectonic joints) or by fractures due to erosion and unloading (sheeting).

Mass movements on anaclinal slopes in Kananaskis Country include rockfalls and rockslides. The accumulation zones of large rockslides can be distinguished from those of rockfalls by their extent and form. Generally, displaced materials from large rockslides display rock sequences similar to those in their depletion zones. Rock blocks from different units in the displaced rock masses are mixed up by rockfalls.

Displaced materials at the toes of the slopes from slope movements can be easily identified on the 1:15840 air photographs covering the study area taken in 1958. Out of those 23 slope movements I identified, 19 slopes were investigated in the field because these 19 have easy access. The discussions of the other slope movements not investigated in the field are based on airphoto interpretation (Table 2.1).

When bedding planes dip at about 65°, large slope movements can occur. The displaced materials at one of the large slope movements, the Elk Ridge slide, indicate that the event was a one-time mass movement, sequence of rocks on the displaced materials follow that on the rockwall. Rupture surfaces of these large slope movements are oblique to both bedding planes and strike joints. Slope movements with less than $0.15 \times 10^6 m^3$ of displaced materials occur where beds dip

Table 2.1 Location and geology of 23 anaclinal slopes and volumes of debris of slope movements

| U.T.M. location (m) Northing | Easting | Geological Formation (Group) | Slope Angle | Bedding Dip | Volume of Debris ($\times 10^6 m^3$) |
|---|---|---|---|---|---|
| 5648500 | 621000 | Dp-Me-Mb-Mr | 50-70 | 20-40 | 0.01 |
| 5645000 | 621700 | Mr | 60 | 30 | 0.02 |
| 5644500 | 623000 | Mr | 60-70 | 20-30 | 0.02 |
| 5643000 | 622900 | Mr | 65-75 | 20-30 | 0.10 |
| 5640800 | 624600 | Mr | 60-70 | 20-30 | 0.01 |
| 5639800 | 619600 | Df | 60 | 20-30 | 0.03 |
| 5637500 | 619600 | Dp | 60 | 30 | 0.01 |
| 5636000 | 620700 | Dp | 60 | 30 | 0.01 |
| 5637700 | 622000 | Mr | 60 | 30 | 0.02 |
| 5633500 | 622000 | Dp | 50 | 35 | 0.01 |
| 5633600 | 623200 | Df | 55 | 30-35 | 0.04 |
| 5631400 | 624700 | Mr | 60-70 | 20-30 | 0.03 |
| 5624500 | 626300 | Prm | 60 | 30 | 0.03 |
| 5622700 | 616800 | Dp | 50 | 40 | 0.04 |
| 5609500 | 621000 | Df | 60 | 35 | 0.03 |
| 5618600 | 623700 | Dp-Me-Mb-Mr | 60 | 65 | 0.01 |
| 5614000 | 625500 | Mr | | | 0.04* |
| 5618300 | 622000 | Mr | | | 0.01* |
| 5607600 | 621700 | Df | | | 0.01* |
| 5630500 | 633200 | Dp | | | 0.02* |
| 5632500 | 611500 | Df-Dp | 45 | 65 | 0.15 |
| 5617000 | 624500 | Mb-Mr | 50 | 65 | 1.10 |
| 5609500 | 638500 | Mr | 45-60 | 65 | 6.09** |

* Not investigated in the field and the volumes from airphoto interpretation.

** Elk Ridge slide.

The UTM locations are from the topographic maps 82J/11 and 82J/14.

The slope angles are current slope angles.

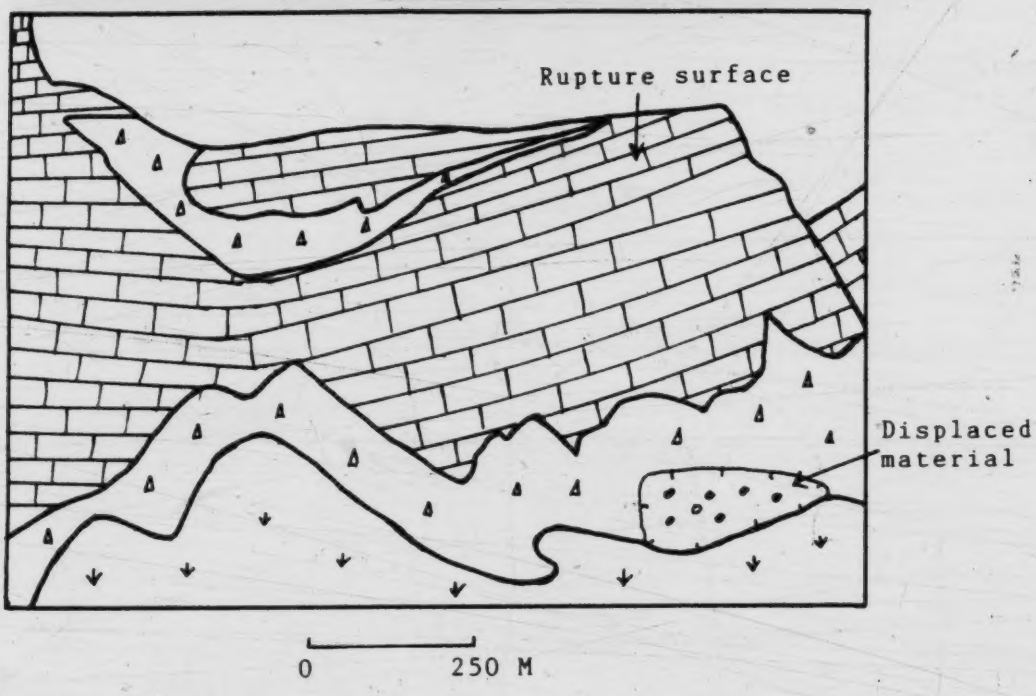
from 20° to 65°. Rupture surfaces of the small slope movements are parallel to strike joints except in one case when the bedding dips at 65°. The 23 slope movements can be then divided into two groups by the volume of their displaced materials using the dividing point of $0.15 \times 10^4$ $m^3$ and are discussed separately.

### 2.3.1 Small slope movements

20 out of the 23 slope movements have volumes less than $0.15 \times 10^4 m^3$. Their displaced material is less than 3 m thick and rock blocks in the displaced materials from different units on the rockwalls are mixed up (Fig. 2.4).

On 15 out of these 20 slopes, the bedding dips are less than 40° and the strike joints dip out of the slopes at more than 50°. Rock blocks can slide along joint surfaces if roughness angles are less than 10° because basic friction angles for the rocks in Kananaskis Country are under 42 degrees (Cruden and Hu, 1988, Hu, 1987). The angles of these slopes are generally close to the dips of the strike joints. As the rupture surfaces of the slope movements followed strike joints, these slopes were steepened escarpments before sliding or falling and the strike joints daylighted on the slopes.

The relatively small volumes of the displaced material are a consequence of the steep, closely-spaced rupture surfaces, with limited roughness angles and no cohesion at the scale of the mass movements. Since the last glaciation,




The slope movement is below the Fortress Mountain and in the Rundle Group. The UTM coordinates are 5631400 (northing) and 624700 (easting).

Figure 2.4 A typical example of small slope movements

a limited volume of rock debris accumulated on the slope to cover the ground as thin layers. Rock blocks in the displaced materials on the slopes from all the units on the rupture surfaces or rock walls are mixed up, which indicates that the slope movements were not single sliding events but fragmental rockfalls over a period of time. On the rockwalls of all the small slope movements, there are no discontinuities dipping out of the slopes and daylighting on the slope with displaced rock masses larger than $0.15 \times 10^4$ $m^3$ on them.

On one of the 20 slopes, the bedding dip is 65° (Table 2.1). So small slope movements can also develop when the bedding dips at more than 40°. The movements now may not only be slides on strike joints but also topples of blocks from bedding or a combination of both of them.

Slope angles of anaclinal slopes do not change noticeably because the volumes of displaced materials are small and sliding surfaces are almost parallel to slope surfaces.

The other four slope movements (Table 2.1) also have small volumes determined from the air photographs. They are far from the road and were not investigated in the field so neither bedding orientation nor slope angle could be determined precisely (Table 2.1).

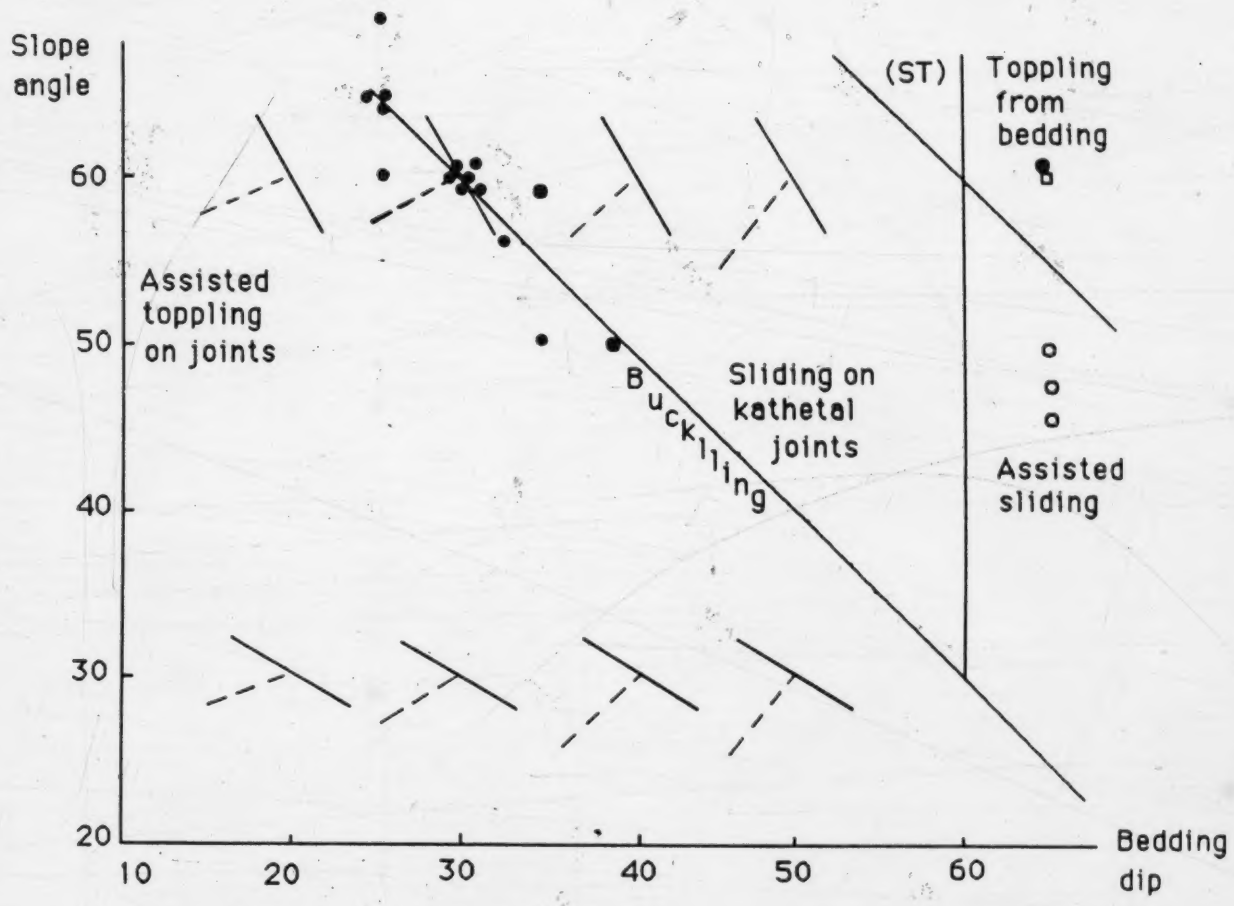
In summary, although slope movements of small magnitude are not restricted to slopes where bedding planes dip into slopes at less than 40°, the events where the bedding dips

at less than 40° considerably outnumber those where the bedding dips are larger than 40°. It is reasonable to conclude that the most common type of small anaclinal slope movements is rockfall with bedding dipping at less than 40° following sliding along strike joints daylighting on steepened or normal escarpments (Fig. 2.5) because rock slopes where bedding dips less than 40° do not dominate the sample of anaclinal slopes in Kananaskis Country. On Fig. 2.5, the lines dividing different areas are from the process diagram (Cruden, 1987, Fig.5) assuming that the friction angle is 30° and cohesion is zero. All the small slope movements except that with the bedding dip of 65° are within 5° of the dips of strike joints, i.e., the slopes are close to normal anaclinal slopes.

### 2.3.2 Large slope movements

Three rockslides have volumes $0.15 \times 10^4 m^3$ or larger (Table 2.1). The bedding dips of the rocks around these three slope movements are 65° dipping into the slope. Both the slope surfaces and the rupture surfaces are oblique to strike joints as well as bedding surfaces. The rupture surfaces have different dips compared with the slopes before the movements, which is not the case for movements of small magnitude (Fig. 2.5).

The rockslide east of Elk Ridge is analyzed further because the displaced material from the rockslide east of Elk Ridge is clearly from one big event and the displaced




(ST): Both toppling and sliding can occur based on the process diagram (Cruden, 1987, Fig. 5).

• Small slope movements, slope angles remain same after sliding.

▫ Original slopes of large slope movements.

o Current slopes of large slope movements.

—— Slope surfaces.

- - - Bedding planes.

Figure 2.5 Relationship between bedding dips and slope angles for slope movements on anaclinal slopes

material looks fresher than at the other two slides. The analysis of the Elk Ridge slide starts with a detailed description of the slide and is followed by back analyses using a toppling model and a sliding model.

## 2.4 Detailed description of the slide east of Elk Ridge

The slide occurred in both the Livingstone Formation and the Mount Head Formation in the hanging wall of the Lewis Thrust (Fig. 2.6). In the footwall of the thrust are Mesozoic sandstones and shales. The west slope of the valley has been steepened by glaciation to form slopes at 60°, which are preserved north and south of the slide.

MacQueen and Bamber (1968) divided the Mount Head Formation into six members. The Salter, Loomis, Opal and Carnavon members are exposed on the rockwalls in the study area (Sauchyn, 1984). The rocks of the Mount Head Formation from the rockwall on the east slope of the Elk Ridge consist of fine to coarse-grained, thinly to thickly bedded limestones and dolostones.

The bedding planes dip at 65°-70° to 240° (represented as 65°-70°/240°) and there are strike joints and dip joints whose orientations are 20°-25°/060° and 90°/150°. The beds in the Livingstone Formation are 40-60 cm thick. The spacing between the strike joints extending across beds of 40-60 cm thick in the Livingstone Formation is 1.5-2 m. Joint spacing is a few centimetres for joints extending less than 5 cm. The rock mass of the Livingstone Formation is strong,

Fig. 2.6. Geology around the Elk Ridge rockslide
The figure is based on the airphoto
AS 748 5027 80 (1:15840).
**A**: The point is five km north of the
Highwood Pass parking lot along Highway
#40.

362 5027 123
32-3-11 50° 37' 115,840 25-8-58
IR AS 748 5027 80

fossiliferous, coarse-grained, light-grey limestone. Sheeting or unloading joints are clearly developed. They are subparallel to the slope surface (Fig. 2.7).

The bedding thickness in the Mount Head Formation is 40-50 cm and the joint spacing averages 5 cm around the top of the Elk Ridge. Most of the rockwall is not accessible. From the descriptions by MacQueen and Bamber (1968) and Sauchyn (1984) and my observations through binoculars, both bedding thicknesses and joint spacings vary from a few centimetres to half a metre. The rock blocks, consisting of grey and yellowish limestones and dolostones, are not considerably weaker than those in the Livingstone Formation from simple field strength tests using a geological hammer (Herget, 1977, p.88). The indentation tests from the samples taken in the study area (Hu, 1987, p.212) showed that 5 samples from the Rundle Group out of total 10 samples have the uniaxial compressive strengths ranging from 160 MPa to 233 MPa. Strike joints are not throughgoing discontinuities but offset against bedding layers, particularly in thickly bedded layers. Sheeting is not seen in this formation.

The east slope of Elk Ridge or rupture surface can be divided into two parts (Figs. 2.8 and 2.9). The lower part, in the Livingstone Formation, slopes at 60°, parallel to sheeting joints. The sheeting joints may extend over 10 m parallel to the slope surface. The upper part of the rupture surface, in the Mount Head Formation, is at 45°. The geomorphological evidence that remains, the scarp, is left

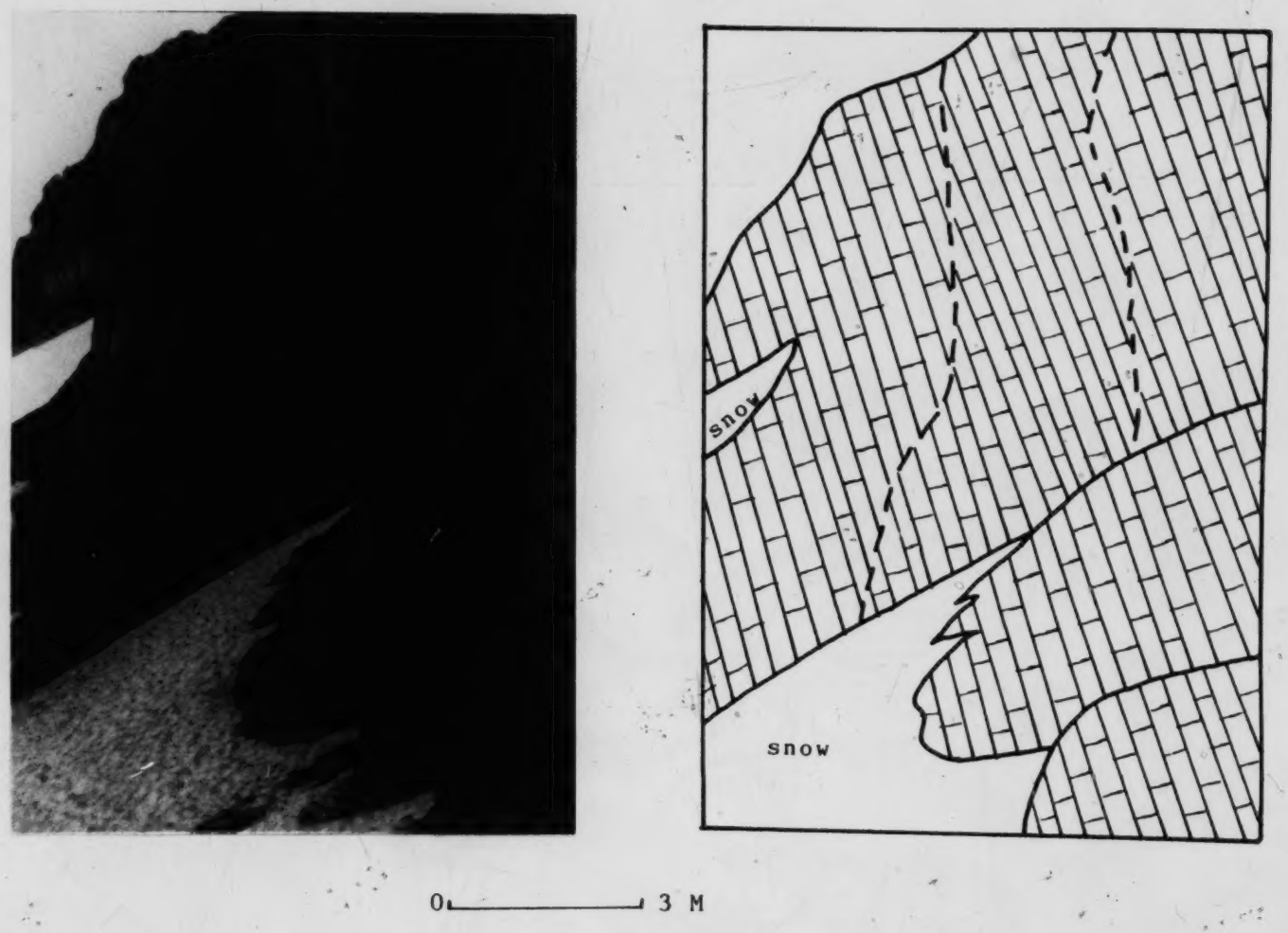
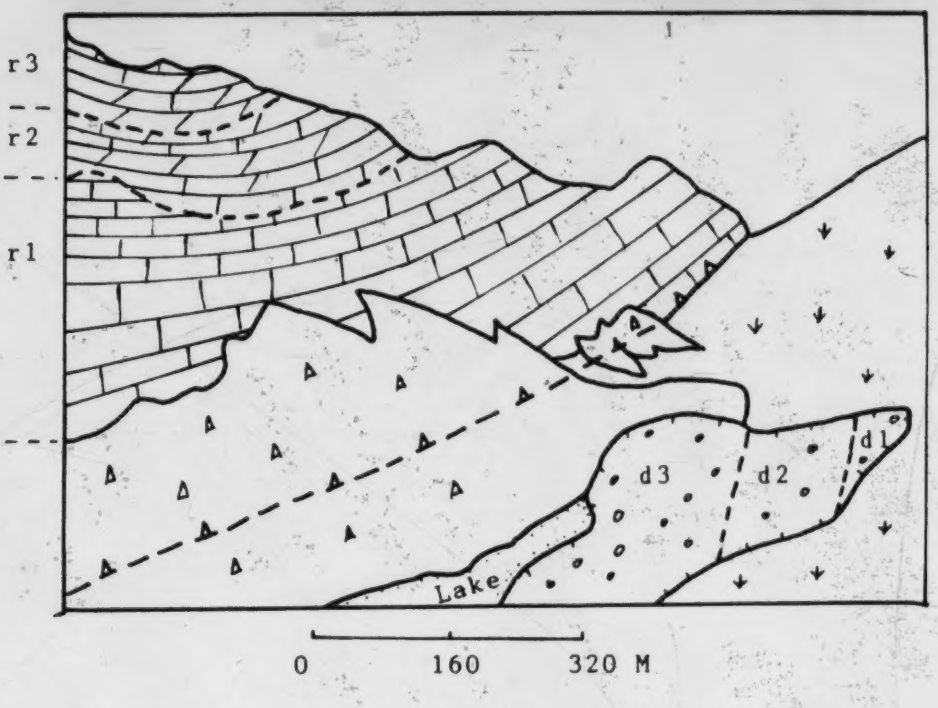



Fig. 2.7. Sheeting joints from the Livingstone Formation below Elk Ridge. Sheeting joints are parallel to slope surface and represented by dashed lines.




Displaced materials d1, d2 and d3 were from r1, r2 and r3 on the rockwall respectively. r1 is in the Livingstone Formation and r2 and r3 are in the Mount Head Formation.

Figure 2.8 The slide from Elk Ridge, with both the debris and the rupture surface

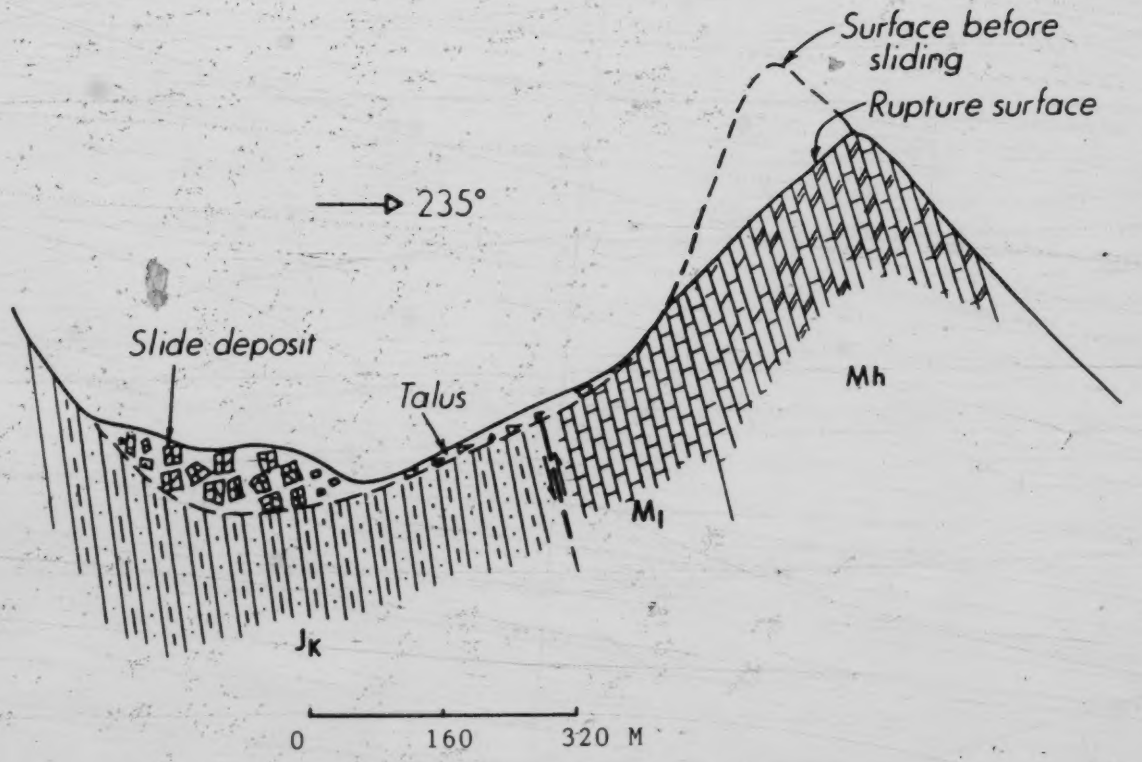



Figure 2.9 Cross-section of the Elk Ridge slide along the sliding direction

only because the slide is old. The sliding surface on the upper part of the slope is oblique to both the bedding surfaces and the strike joints. During the last glaciation, the valley walls were steepened. After the glaciation, the rock mass at Elk Ridge slid along the rupture surface which had the orientation of the current slope but is highly weathered now.

The displaced materials (Fig. 2.8) show the stratigraphic sequence on the rupture surface from which the displaced rock mass came. The rock sequence in the debris and that on the sliding surface is the same. This suggests the deposit resulted from a single big event, not from the accumulation of numerous rock falls from different strata over a period of time. The vegetation on the debris is not well developed, which may indicate the slide is hundreds rather than thousands of years old. The volume of the debris is estimated as $6 \times 10^4$ $m^3$ by multiplying the area of the cross-section in Fig. 2.9 by the length of the materials along the valley. Gardner *et al.* (1983, p.87) identified the debris east of Elk Ridge and considered it was a large rockfall.

The travel angle, the arc-tangent of the ratio of vertical displacement to horizontal displacement of the centre of displaced materials, is 29°, at the boundary of slides and falls (Hungr and Evans, 1989). The slope to the east prevented the debris travelling further eastward and may explain the comparatively large travel angle.

According to Heidebrecht and Tso (1985), the peak horizontal seismic acceleration is 0.04g in the study area, which suggests that seismic activities may have contributed to initiation of some slope movements.

## 2.5 Back analysis of the slide east of the Elk Ridge

### 2.5.1 Assumptions and selections of the models for calculation

The original slope should dip at 60° because the slopes where there are no rockslides on the east slope of Elk Ridge are about 60° around the slide. On the lower part of the slope, sheeting joints parallel the slope surface. So it is reasonable to consider the lower rupture surface followed the sheeting joints.

There are no sheeting joints in the Mount Head Formation. The rupture surface is oblique to both bedding planes and strike joints. It is possible for toppling from bedding planes to develop on the original slope based on bedding orientations and slope angles (Fig. 2.5). Sliding along the rupture surface of the topple may follow toppling with the displaced materials deposited at the toe of the rock slope.

In the Mount Head Formation, the ratio of joint spacing of the strike joints to the bedding thickness (h/b) is less than 1/5 around the top of the Elk Ridge. But this ratio in the Mount Head Formation may vary a lot. Aydan *et al.* (1989)

indicated that offset of cross fractures can considerably increase minimum slope angles for toppling determined for throughgoing cross fractures. The increase is controlled by an intermittency parameter which is a function of the spacings and arrangements of discontinuities (Aydan *et al.*, 1989). The thin and thick bedding layers with varied joint spacings and arrangements in the Mount Head Formation may prevent some parts of the rock mass with large intermittency parameters from toppling. So the displaced rock masses may have slid along the current slope surface.

The slide may have been triggered by seismic activities along the Lewis Thrust. There is another large slope movement along the Lewis Thrust in Montana (Butler, 1983) considered to be triggered by an earthquake.

In a simple analysis of rock masses sliding along one set of discontinuities and separating from undisturbed rock masses along another set of discontinuities, a stepped rupture surface forms but the overall slope angle after sliding cannot be predicted. For the large slides in the study area, the dip angles of the rupture surfaces of the three events and bedding dips are similar (Table 2.1), the dip angles of their rupture surfaces should relate to geological structure on these anaclinal slopes.

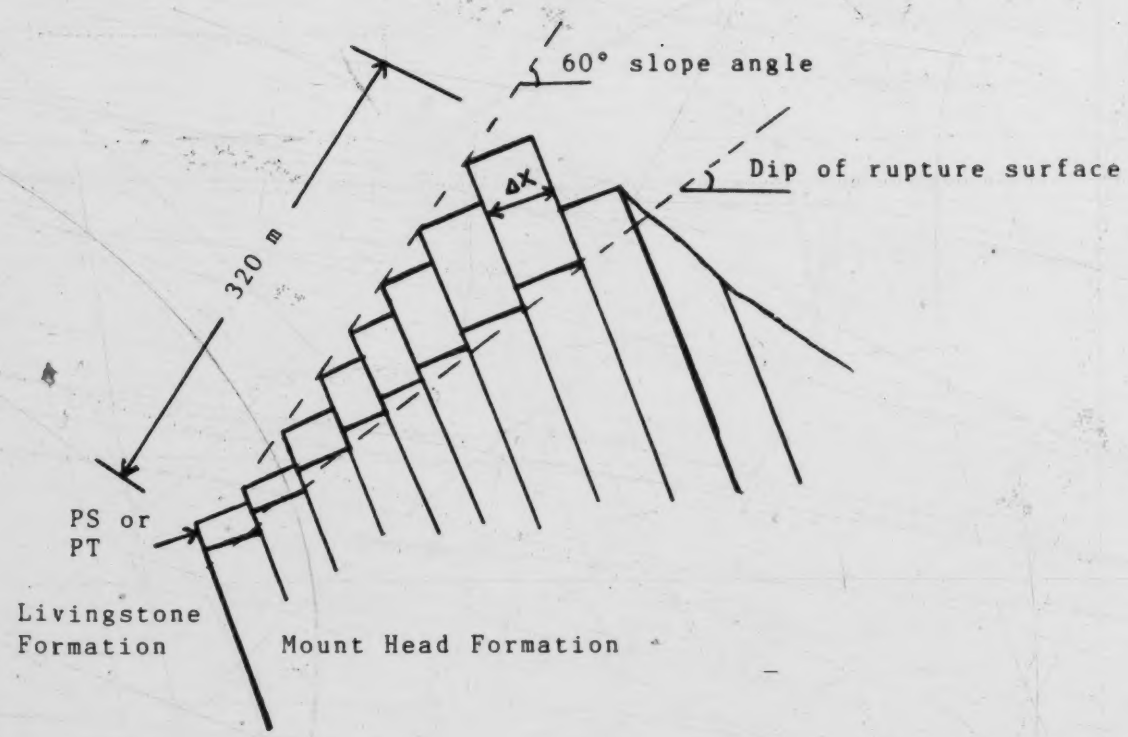
To evaluate stability of the original slope with respect to both toppling and sliding, I have used both the block toppling model of Goodman and Bray (1976) and a sliding model based on the model tests of Ladanyi and

Archambault (1970) and modified by Hoek and Bray (1977).

### 2.5.2 Toppling model

In the block toppling model of Goodman and Bray (1976), the potential topples are divided into a number of blocks with discontinuities parallel to penetrative discontinuities in the rock masses. The rupture surface is a combination of cross fractures and penetrative discontinuities but the overall orientation of the rupture surface can only be assumed. The forces acting on each block are calculated from the top of the slope to the toe of the slope. The external force or support required against toppling or sliding for the toe block is calculated. If the external support against toppling or sliding is larger than zero, the slope is not stable with respect to toppling or sliding. The results of the calculation are dependent on friction angles of discontinuities, dip angles of rupture surfaces and block thicknesses. Dip angles of rupture surfaces and slope angles determine volumes of toppled or potential toppled rock masses. The assumed geometry of the slope for toppling analysis is shown in Fig. 2.10.

Because the rocks in the Mount Head Formation are laminae of fine to coarse-grained limestones and crystalline dolostones, their basic friction angles are not likely to exceed 40° (Hu, 1987). In the back analyses, friction angles of 25°, 30°, 35° and 40° are selected for calculation. Friction angles are assumed to be the same for bedding




PS and PT are forces to cause sliding or toppling of the toe block.

Figure 2.10 Assumed geometry of the slope for toppling analysis

planes and joints. Cohesion is assumed zero in the model considering that weathering and tectonics have destroyed or will eventually destroy cohesion along discontinuities.

The dip angles of rupture surfaces are assumed to be 27°, 30°, 33°, 36°, 39°, 42°, 45°, 48°, 51°, 54° and 57° in the model to study potential movements over these rupture surfaces.

It is generally not possible to know how many "intact" blocks were involved in toppling and toppled block thicknesses may not be the same as in the real situation. Some of the rock blocks in the displaced materials after the original blocks were smashed were as big as 5 m in diameter, so it is reasonable to consider some of the "intact" block before sliding were more than 5 m thick. In the model, constant block thicknesses of 10 m, 15 m and 20 m are assumed in the calculations.

The back analysis is conducted with all the above parameters and the results indicate that the toe block of the original slope was unstable against toppling or sliding in most of the combinations of the above parameters (Table 2.2). In Table 2.2, the positive forces are those required for support. The toe block may be supported by rock layers in the Livingstone Formation. After the support from the layers of the Livingstone Formation was removed by sliding along sheeting joints or toppling, the toe block in the Mount Head Formation could be moved by toppling or by sliding. After the toe block is removed, the other blocks

Table 2.2 The results of back calculations using a toppling model

| ΔX | PHI | DIP | 27 | 30 | 33 | 36 | 39 | 42 | 45 | 48 | 51 | 54 | 57 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 25° | PT | -2344 | -744 | -325 | -122 | 55 | 377 | 224 | 604 | 628 | 5888 | 10 |
| | | PS | 414 | 466 | 495 | 612 | 859 | 1601 | 5245 | 1343 | 1206 | 10686 | 17 |
| | 30° | PT | -594 | -97 | 35 | 103 | 167 | 279 | 149 | 229 | 180 | 627 | 41 |
| | | PS | 241 | 254 | 249 | 274 | 325 | 465 | 223 | 321 | 239 | 805 | 51 |
| | 35° | PT | 143 | 129 | 111 | 103 | 93 | 75 | 82 | 48 | 36 | 149 | 237 |
| | | PS | 127 | 122 | 107 | 100 | 91 | 74 | 81 | 47 | 36 | 145 | 235 |
| | 40° | PT | 391 | 184 | 117 | 87 | 65 | 42 | 191 | 26 | 15 | -8 | -7 |
| | | PS | 74 | 68 | 55 | 48 | 40 | 27 | 136 | 18 | 11 | -7 | -6 |
| 15 | 25° | PT | -1794 | -523 | -247 | -79 | 40 | 242 | 122 | 318 | 251 | 641 | 11 |
| | | PS | 321 | 320 | 383 | 415 | 590 | 1021 | 337 | 705 | 480 | 1109 | 17 |
| | 30° | PT | -470 | -63 | 34 | 79 | 127 | 196 | 92 | 134 | 78 | 7 | X |
| | | PS | 199 | 188 | 206 | 202 | 243 | 322 | 135 | 186 | 102 | 8 | X |
| | 35° | PT | 147 | 112 | 105 | 87 | 80 | 60 | 87 | 37 | 33 | 5 | X |
| | | PS | 112 | 98 | 96 | 81 | 75 | 57 | 84 | 35 | 32 | 4 | X |
| | 40° | PT | 361 | 152 | 104 | 67 | 50 | 27 | 138 | 6 | -11 | -13 | X |
| | | PS | 61 | 50 | 45 | 33 | 27 | 14 | 97 | 2 | -11 | -13 | X |
| 20 | 25° | PT | -1244 | -440 | -170 | -49 | 32 | 162 | 74 | 123 | 39 | 10 | 11 |
| | | PS | 229 | 277 | 275 | 285 | 411 | 668 | 197 | 268 | 72 | 16 | 17 |
| | 30° | PT | -318 | -46 | 33 | 63 | 96 | 133 | 58 | 47 | 21 | 14 | X |
| | | PS | 149 | 169 | 156 | 145 | 176 | 214 | 81 | 62 | 26 | 16 | X |
| | 35° | PT | 150 | 116 | 91 | 72 | 66 | 46 | 106 | 23 | 31 | .2 | X |
| | | PS | 87 | 90 | 75 | 60 | 57 | 40 | 101 | 19 | 29 | -2 | X |
| | 40° | PT | 304 | 148 | 86 | 51 | 34 | 11 | 102 | -14 | -29 | -20 | X |
| | | PS | 42 | 42 | 30 | 19 | 12 | -.5 | 68 | -15 | -27 | -18 | X |

ΔX: Block thickness, in metres.
PHI: Assumed friction angles.
DIP: Dips of different base rupture surfaces, in degrees.
PT: Forces to cause toppling of the toe blocks, in MN, assuming unit width.
PS: Forces to cause sliding of the toe blocks, in MN, assuming unit width.
X: PS or PT can not be calculated because all the individual blocks are not subject to toppling.

can be removed by toppling or sliding and finally the rock masses above the rupture surface are displaced along the rupture surface.

Table 2.2 shows that except when the friction angle is 40° and the dips of the rupture surfaces are steeper than 48°, the toe block is unstable either by toppling or by sliding. The required supporting forces for either toppling or sliding decrease with an increase in friction angle and also decrease with an increase in the block thickness. There are no clear trends for the supporting forces dependent on the dips of the rupture surfaces.

### 2.5.3 Sliding models

If sliding is the movement mode, the rupture surface might be a combination of the strike joints and bedding surfaces in the Mount Head Formation, with shearing along the strike joints and separation along bedding planes (Fig. 2.11). In the Livingstone Formation, sliding follows sheeting joints.

Since the rupture surface is not a plane but a combination of two planes for the whole movement, the movement may not be a simple slide. Suppose the displaced rock mass is in two parts, one in the Livingstone Formation and the other in the Mount Head Formation. As the kinematically active discontinuities are sheeting joints and the combination of bedding surfaces and strike joints with sliding on the strike joints, the part of the rock mass in

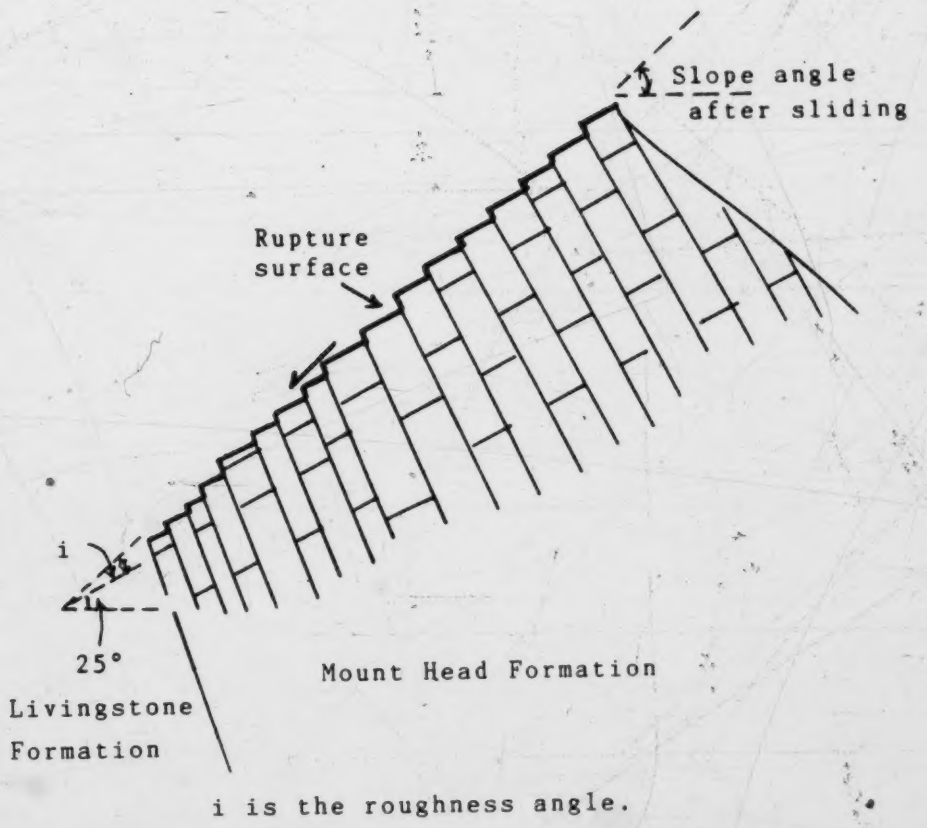



Figure 2.11 Assumed sliding surface of the Elk Ridge rockslide in the Mount Head Formation

the Livingstone Formation may have supported the part in the Mount Head Formation before sliding. Because the rupture surface in the lower part is parallel to the slope surface and sheeting joints are close to the slope surface, the volume of the lower part is considerably smaller than the upper part. Sliding of the lower part may trigger sliding or toppling of the upper part. Once the lower part was removed or slid, the upper part slid or toppled following its own rupture surface.

If the rock mass did not slide along any individual discontinuity, the rock mass can be considered as highly fractured and there was possibly some crushing around corners of blocks while sliding. Then Ladanyi and Archambault's equation as modified by Hoek and Bray (1977, P.104) can be used to back calculate the stability of the slope. The equation is as follows,

$$\tau = \frac{\sigma(1-a_s)(\dot{v}+\tan\phi)+a_s\eta\sigma_b\frac{\sqrt{1+n}-1}{n}\left(1+n\frac{\sigma}{\eta\sigma_b}\right)^{1/2}}{1-(1-a_s)\dot{v}\tan\phi} \qquad (1)$$

where

$\dot{v}=(1-\sigma/\sigma_c)^k\tan i$

$a_s=1-(1-\sigma/\sigma_c)^L$

and $\sigma_c$ is the uniaxial compressive strength of the individual blocks within the rock mass,

$\eta$ is the degree of interlocking which defines the freedom of the blocks to translate and to rotate before being sheared or fractured,

$\tau$ is shearing resistance,

$\sigma$ is normal stress,

$\phi$ is friction angle,

i is the roughness angle,

n is equal to 10.

k and L are determined by modes of failure.

Ladanyi and Archambault (1970) proposed three modes of failure of highly fractured rocks. (1) Shear along a well defined plane inclined to both discontinuity sets, (2) Formation of a narrow zone in which block rotation has occurred in addition to the sliding and material failure of Mode 1 and (3) Formation of a kink band of rotated and separated columns of 3, 4 or 5 blocks.

For back analysis, the slide is assumed to be either a mode 1 failure or mode 2 failure because the rupture surface is nearly planar and no signs of the formation of a kink band are found. Hoek and Bray (1977) suggested that for mode (1), K=4, L=1.5 and $\eta$=0.7 and for mode (2), K=5, L=tan$i$ and $\eta$=0.6.

In the stability analysis using equation (1), rupture surfaces were assumed to determine along which inclined plane the original slope is weakest. The ratio between the shear resistance and the shearing driving force was calculated for all these assumed rupture surfaces.

The original ground surface slope is assumed to be 60°, which is the same as the slopes where there are no slides along the east side of Elk Ridge. The dip angles of the

assumed rupture surfaces ranged from 55° to 25° with an interval of 1°. Because sliding is assumed to occur along the strike joints, the angle between the overall sliding direction and the direction of the dip of the strike joints is the roughness angle i, which ranges from 30° to 0° for the above assumed rupture surfaces (Fig. 2.11).

The rocks in the Mount Head Formation are mainly fine and coarse-grained limestones and crystalline dolostones, friction angles of 25°, 30°, 35° and 40° were used based on the studies of the friction angles of carbonates and clastic rocks in Kananaskis Country by Hu (1987).

The uniaxial compressive strengths of the carbonates are determined by NCB cone indentation tests on fresh rock-sawn surfaces of samples. Uniaxial compressive strengths are between 160 and 230 MPa. Due to weathering and weakening around discontinuities, the actual uniaxial compressive strengths of the rock blocks may be lower. According to Hoek and Bray (1977, p.107), the uniaxial compressive strength used in equation (1) should be a quarter of that of unweathered intact rocks. So $\sigma_c$=40MPa and 60MPa are used for the analysis.

The geometry of the slide in the analysis is shown in Fig. 2.12, here the average driving shearing stress along the rupture surface is

$$\tau_{driving}=(W\sin\alpha_1)/(R\cdot 1)=\gamma R\alpha_2\sin\alpha_1/2$$

and the average normal stress along the assumed rupture surface is

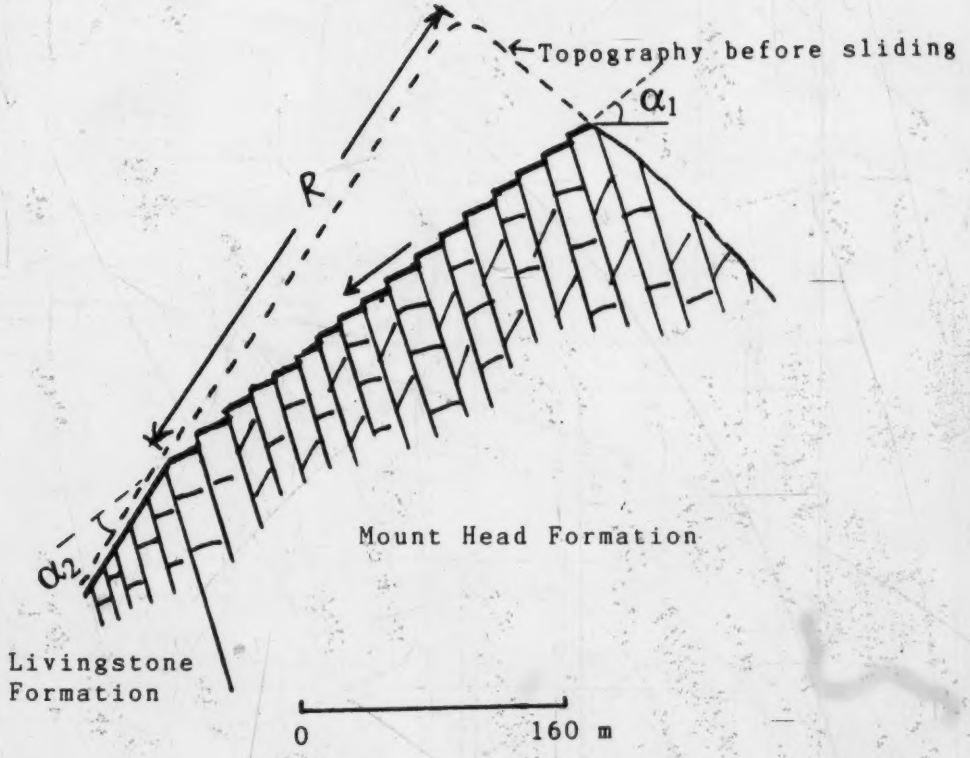
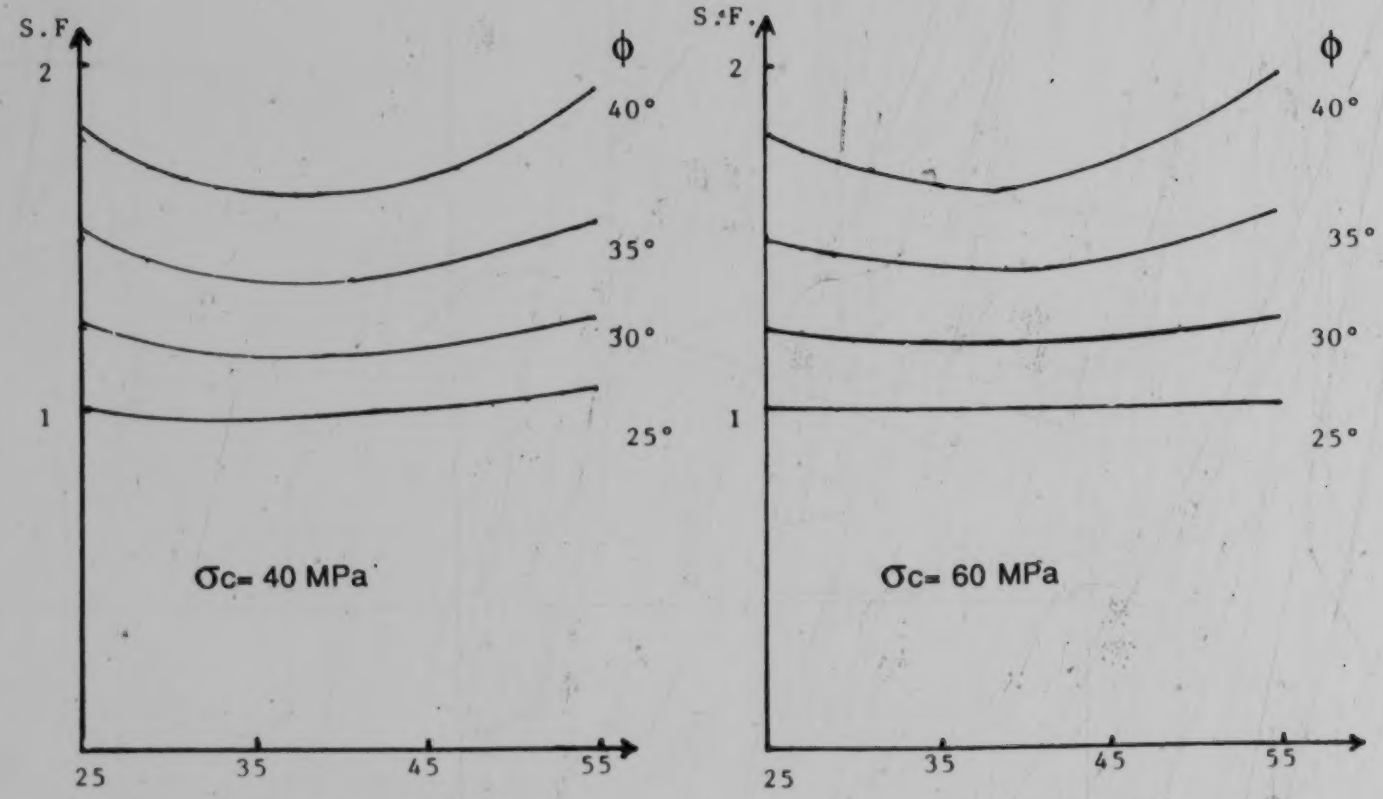



Figure 2.12 Assumed topography before sliding and rupture surface for back analysis

$$\sigma_n=(W\cos\alpha_1)/(R\cdot 1)=\gamma R\alpha_2\cos\alpha_1/2$$

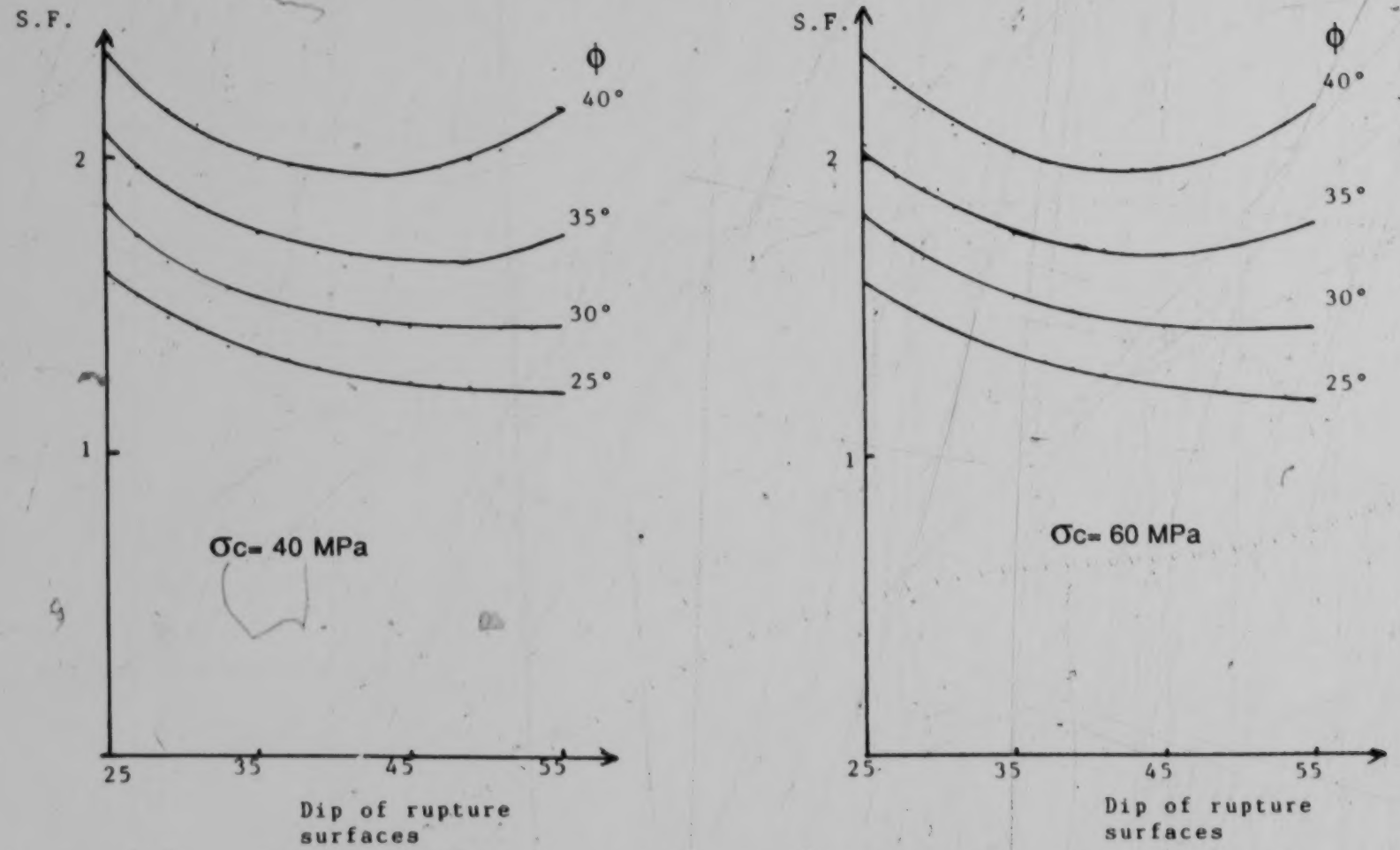
where $\gamma$ is the unit weight of the rock mass, 25 KN/m$^3$. W is the weight of the sliding rock mass of unit width. $\alpha_2$ ranges from 5° to 35°. The length of the rupture surface in the Mount Head Formation in the sliding direction is assumed to be equal to the length of the slope surface in the Mount Head Formation in the sliding direction before sliding.

In the back calculations, shear stresses and normal stresses are assumed constant along the rupture surfaces and equal to the average values. The ratios of the resistant shearing stress and the driving shearing stress or the factor of safety are calculated for different rupture surfaces. With all the variations of the uniaxial compressive strengths and the friction angles, when the dip of the assumed rupture surface is between 35 and 45°, the ratio reaches the minimum for failure mode 2 (Fig. 2.13). So if the rock masses slide in failure mode 2, the rupture surface dips at between 35° and 45°. The factor of safety reaches a minimum between 40° and 50° for failure mode 1 when the friction angles are 35° and 40° and there is no minimum factor of safety for failure mode 1 when the friction angles are 25° and 30° (Fig. 2.14) Except when the friction angle is 25° in mode 2, the factors of safety are larger than one. So the failure may have been assisted by some forces other than gravity such as seismic forces and pore pressures at the beginning of the event.




S.F. : Ratio of resisting force to sliding driving force or factor of safety.

Fig. 2.13. Relationship between factor of safety, friction angles, and dips of rupture surfaces for mode 2 of the sliding model.




S.F. : the ratio of resisting forces to sliding driving forces or factor of safety.

Fig. 2.14. Relationship between factor of safety, friction angles, and dips of rupture surfaces for mode 1 of the sliding model.

There is no direct evidence to show whether the failure by sliding was mode 1 or mode 2 when sliding. The values of K and L in equation (1) may not be the same for different discontinuity spacings and uniaxial compressive strengths in different units along the rupture surface. The back analyses only give simplified results for the sliding models. Unlike slides along penetrative discontinuities, sliding surfaces on anaclinal slopes are determined by several factors, such as discontinuity orientations, friction angles, topography and probably external forces. The current slope angle, 45°, of the Elk Ridge slide may be the result of a combination of the above factors.

Since the factors of safety for most of the combinations of the friction angles, the dips of rupture surfaces and the uniaxial compressive strengths are larger than one, sliding may not be as critical as toppling.

### 2.5.4 Summary

From the results of the kinematic analyses, large volumes of rock masses on steepened anaclinal slopes can be displaced by either sliding along combinations of discontinuities or toppling then sliding along rupture surfaces. But orientations of sliding surfaces or rupture surfaces of topples cannot be simply determined by these back calculations. In the sliding model, sliding occurs on different surfaces depending on friction angles of discontinuities, orientation of discontinuities, rock

strengths and movement modes. In the toppling model, the supporting forces required for stable toe blocks for a certain rupture surfaces are functions of block structures, frictional properties and topography.

## 2.6 Conclusions

The research is a first evaluation of the stability of anaclinal slopes in stratified rocks in the Canadian Rockies. The stability of these slopes and the magnitude of the events are controlled by their geological structures as well as lithologies which determine the strength of the rocks.

In the Paleozoic carbonate rocks and clastic rocks in the study area, the orientations of the discontinuities control the magnitude of slope movements. Large slides are found where the bedding planes dip into the slope at about 65°, the strike joints dip out of the slope at about 25° and the slopes are 60°. Sheeting can form the rupture surface where the rocks are strong and have large joint spacings.

Depending on discontinuity spacings and arrangements, it is kinematically possible for large slope movements from a steep slope to be either toppling or sliding along a combination of bedding surfaces and strike joints. Analysis of the Elk Ridge slide indicates that catastrophic movements can occur along the rupture surfaces of topples or slides on anaclinal slopes. An analysis of toppling can be conducted by Goodman and Bray's model (1976) and an analysis of

sliding along combinations of discontinuities can be conducted by Hoek and Bray's (1977) modification of Ladanyi and Archambault's (1970) model. However, both methods require assumptions for which there is no field evidence to determine parameters for the models. Only one assumption, the number of columns is required for toppling to occur in the toppling model and the model is not very sensitive to variation in the number of columns. The model indicates failure over a wide range of possible values and is apparently a more conservative choice for the back analysis of these very steep anaclinal slopes than sliding models.

Most of the small events occur where bedding is gentler than 40° while the strike joints are steeper than 50°. Small rock falls initiated by sliding are the main type of small slope movement.

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# 3. Topples on cataclinal, underdip slopes in Kananaskis Country, Alberta

## 3.1 Introduction

Topples have received a lot of interest, particularly in recent years. All of the work has been done on topples on anaclinal slopes (De Freitas and Watters, 1973; Goodman and Bray, 1976; Choquet and Tanon, 1986). On anaclinal slopes, penetrative discontinuities dip into slopes and the driving force for toppling is mainly gravity.

Tang (1986) found topples in steeply dipping strata on underdip, cataclinal slopes in the Highwood Pass in Kananaskis Country, Alberta. Cruden (1989) showed that topples can occur on a much wider range of slopes than that predicted by Goodman (1980) with the same assumptions as Goodman and Bray (1976) made. He indicated that toppling can occur on underdip slopes without any external assistance.

In order to understand mechanisms of toppling on underdip, cataclinal slopes, to evaluate the stability of underdip slopes and to study the evolution of underdip slopes, I investigated the topples found by Tang (1986) during the summers of 1988 and 1989.

In this chapter, I report for the first time features and characteristics of these topples, analyze geological controls of toppling and explain the processes of toppling on underdip cataclinal slopes.

## 3.2 Field investigations and bedrock geology

### 3.2.1 Field investigations

I investigated topples in the Highwood Pass, Kananaskis Country east of Highway #40. As different topples have different deformation features even when they are close together, toppled rock masses are described by sites. Within a site, toppled rock masses have the same deformation style as well as similar geology.

The investigation at each site included:

1. Deformation styles of topples, including orientation changes of discontinuities caused by toppling and relative displacements of rock blocks in toppled rock masses.
2. Discontinuities formed by toppling.
3. Lithology.
4. Strength of rock masses, which are estimated by the methods described by Herget (1977, p. 88).
5. Topography which determines the stress state at the surface of rock masses.

Sixteen toppling sites were investigated (Figs. 3.1-3.3). All of them are on a NW-SE ridge trending parallel to the strikes of the bedding planes. The ridge is dissected by a number of NE-SW trending gullies.

Rock layers of the topples have experienced more rotation than topples on anaclinal slopes before sliding of toppled rock masses can occur. Most toppled layers rotated

Fig. 3.1. Geology around the toppling sites #1-#8.
The figure is based on the enlarged airphoto AS 748 5028 128 (1:5280).
Point "A" is 5.2 km north of the Highwood Pass parking lot along Highway #40.
C1-C4: the creeks.
Toppling sites are numbered as T1-T8.

T1

Fig. 3.2. Geology around the toppling sites #9-#12.
The figure is based on the enlarged airphoto AS 748 5027 82 (1:5280).
Point "B" is 2.25 km north of the Highwood Pass parking lot along the Highway #40.
C5-C9: Creeks.
T9-T12: Toppling sites.

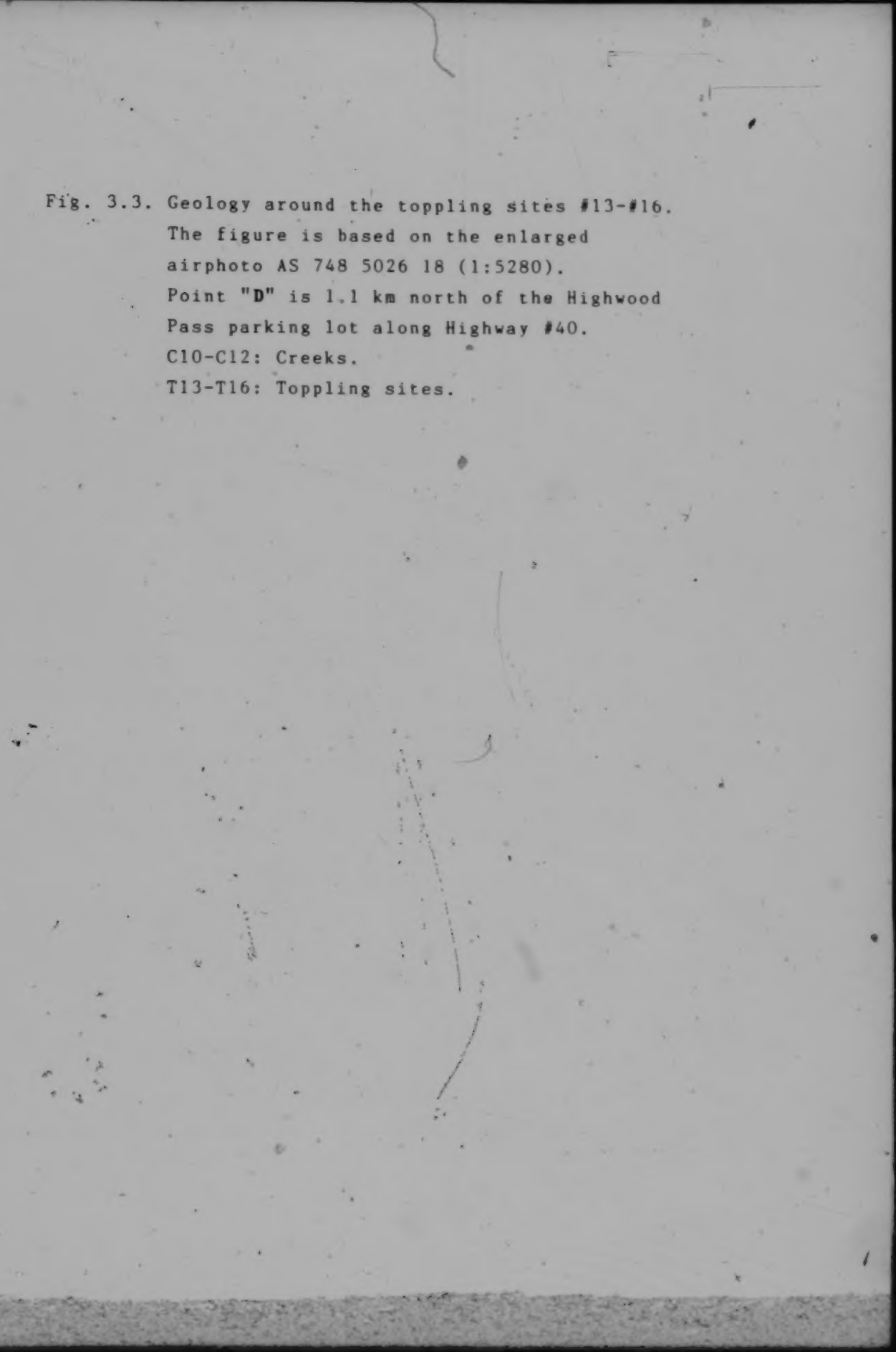


Fig. 3.3. Geology around the toppling sites #13-#16.
The figure is based on the enlarged airphoto AS 748 5026 18 (1:5280).
Point "D" is 1.1 km north of the Highwood Pass parking lot along Highway #40.
C10-C12: Creeks.
T13-T16: Toppling sites.

more than 40°. Several different deformation styles are found with different geological structures, strengths of rock blocks and topography.

Topples on underdip slopes have unique features such as hinge surfaces connecting hinge lines, sliding surfaces along which rock masses can be displaced and steep cracks which are more or less parallel to slopes and follow joints. These features have not been reported from topples on anaclinal slopes.

### 3.2.2 Bedrock Geology

The topples from bedding surfaces in Kananaskis Country occur in the Triassic Spray River Formation (Allan and Carr, 1947) which was raised later to Spray River Group (Irish, 1965). The topples are in the Rundle thrust sheet (Bielenstein *et al.*, 1971). Around the topples in Highwood Pass, from the bottom of the Spray River Group, the rocks change from shales to thinly bedded sandstones and sandy limestones to strong calcareous sandstones to laminae of thinly bedded shales and thickly bedded sandstones to thickly bedded sandstones (Fig. 3.4). The geological column (Fig. 3.4) was measured from Creek 1 (Fig. 3.1) and the thicknesses of the units in the Spray River Group in the geological column differ in different creeks (Figs. 3.1-3.3). The boundaries of different units are transitional.

| PERIOD | FORMATION (GROUP) | LITHOLOGY | DESCRIPTIONS | Toppling Sites (Approximately) |
|---|---|---|---|---|
| Jurassic | Fernie | | Shales | |
| Triassic | Spray River | | Medium to thickly bedded sandstones. $\sigma_c$ is greater than 200 MPa. | 2 |
| | | | Thinly to medium bedded sandstones. $\sigma_c$ is between 80 MPa and 200 MPa. | |
| | | | Thinly to thickly bedded calcareous sandstones. $\sigma_c$ is between 80 MPa and 200 MPa. | 1, 10, 6, 3, 7 |
| | | | Thinly to medium bedded sandstones. $\sigma_c$ of the thin layers is less than 80 MPa and $\sigma_c$ of the medium layers is between 80 MPa and 200 MPa. | 4, 8, 13, 14, 5, 15, 9, 11, 12, 16 |
| | | | Shales. | |
| Permo-Pennsylvanian | Rocky Mountain | | Quartzites. | |

The scale is 1:2000.

Figure 3.4 Stratigraphic column in the Spray River Formation in Highwood Pass area

Bedding orientation before toppling is about 70-90°/240°. Toppled layers rotated up to 110° about their strikes. The untoppled bedding planes dip in the same directions as the slopes.

Joints are either perpendicular to bedding planes or sub-parallel to bedding planes. Strike and dip joints are the dominant discontinuities other than bedding planes (Fig. 3.5). The spacings of the joints are generally 10 to 50 cm and the bedding thicknesses vary from 0.5 cm to 50 cm. The ratio of joint spacing to bedding thickness ranges from 1 to over 20. This ratio is represented as h/b in the thesis and is the same as that in DeFreitas and Watters (1973).

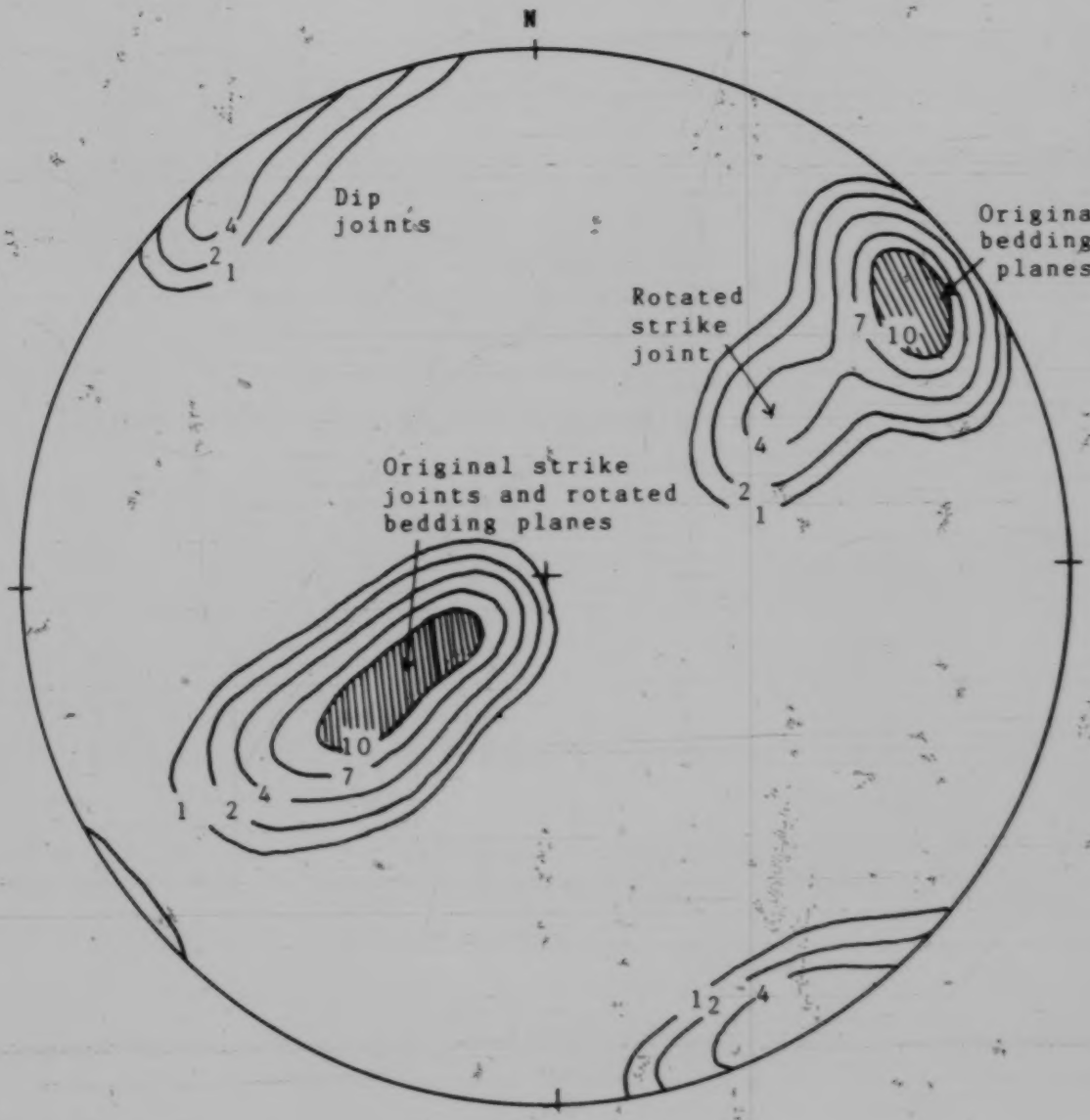
All the rock layers from the Spray River Group are found toppled on the slope surfaces if not covered by vegetation.

### 3.3 Description of topples

The study sites are on the sides of the gullies which dissect the NW-SE trending ridge (Figs. 3.1-3.3). The sites are numbered from north to south and their locations are referred to the locations of gullies or creeks which are also numbered from north to south (Figs 3.1-3.3).

#### 3.3.1 Site #1

The site is located at the north side of the middle of Creek 1 (Figs. 3.1 and 3.4). The bedding planes on the ground surface are rotated from 76°/240° to 70-05°/060°



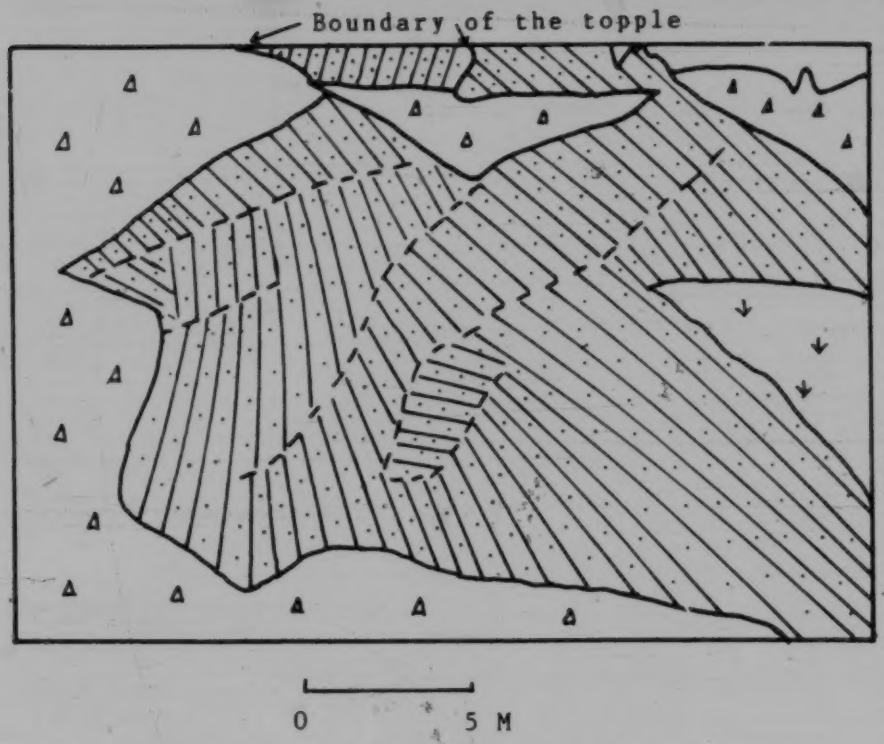

The contour lines are from poles of 115 measurements of discontinuities in the Spray River Formation. Probability diagram (K=100) on an equal angle projection.

Figure 3.5 Structure diagram for toppling sites

about their strike. The dips of the bedding layers change abruptly by more than 10° due to toppling across some surfaces and there are several toppled blocks (Fig. 3.6). There are also some steep cracks at about 60° following combinations of bedding surfaces and strike joints (Fig. 3.6). The rocks are thin to medium bedded, dark brown, weathering, fine-grained sandstones with a few thin shale layers in between. The bedding thickness is 1 to 10 cm with a mode of 2 cm and the joint spacing is 5 to 15 cm with a mode of 10 cm. The average h/b is estimated by the modes of the discontinuities to be about 5. The uniaxial compressive strength is estimated as about 80 MPa. The slope angle is 35° to 40°.

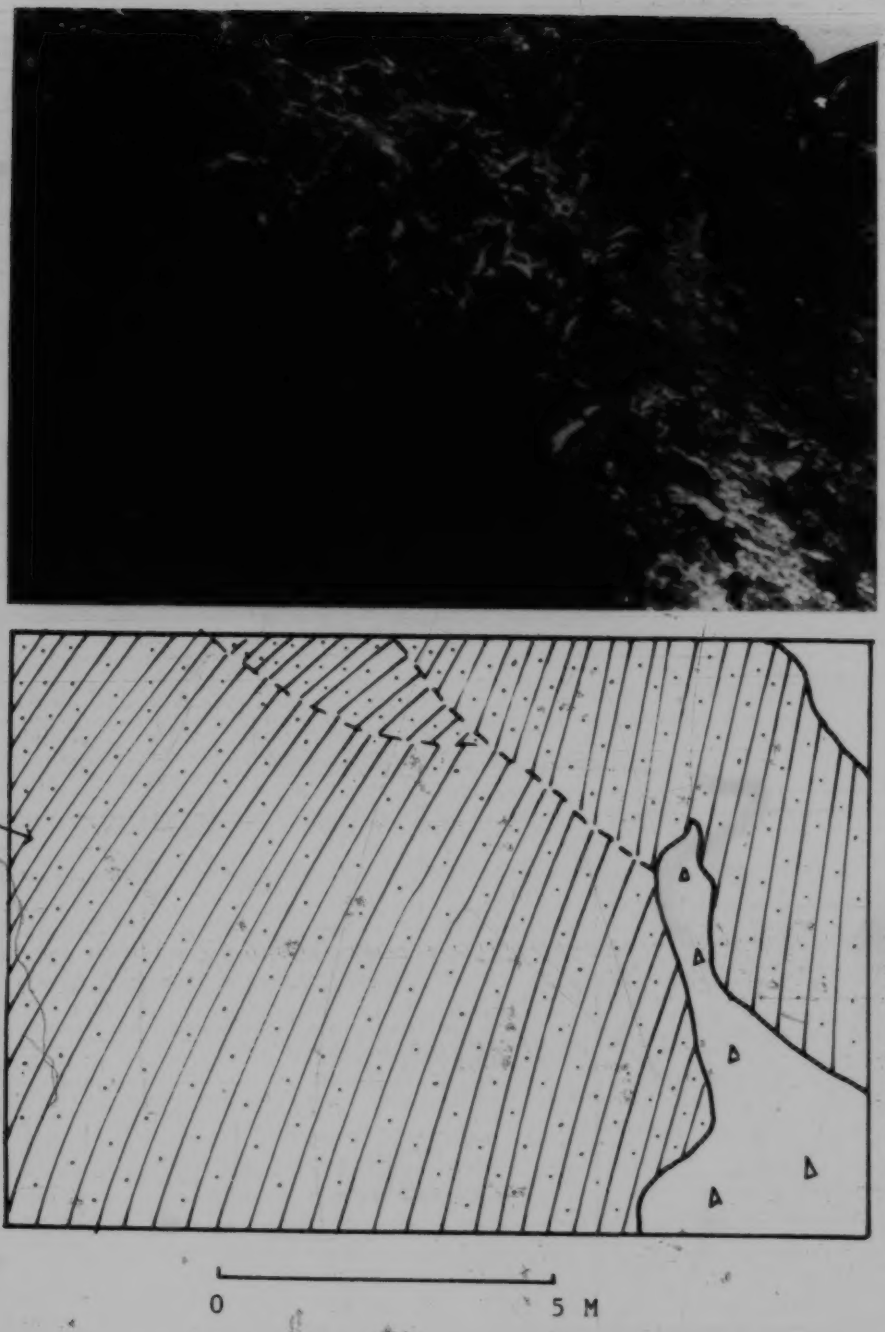
### 3.3.2 Site #2

The site is at the outlet of Creek 1 and is around the toe of the slope (Figs. 3.1 and 3.4). The topple involves both the thickly bedded sandstones and thin to medium bedded sandstones around the boundary of the Spray River Group and the overlying Jurassic Fernie Formation. The layers above the bottom of the creek have all toppled to dip NE. The toppled bedding surfaces show smooth rotations of beds due to toppling (Fig. 3.7). The dips of the toppled layers change gradually from 50° at the bottom of the creek to 37° around the top of the toppled layers without sharp changes of dip angles along bedding layers. The toppled layers form smooth curves. The maximum distance from the bottom of the




The topple is in the Spray River Formation and dashed lines separate different toppled blocks. Solid lines are boundaries of the topple.

Figure 3.6 toppling at Site #1



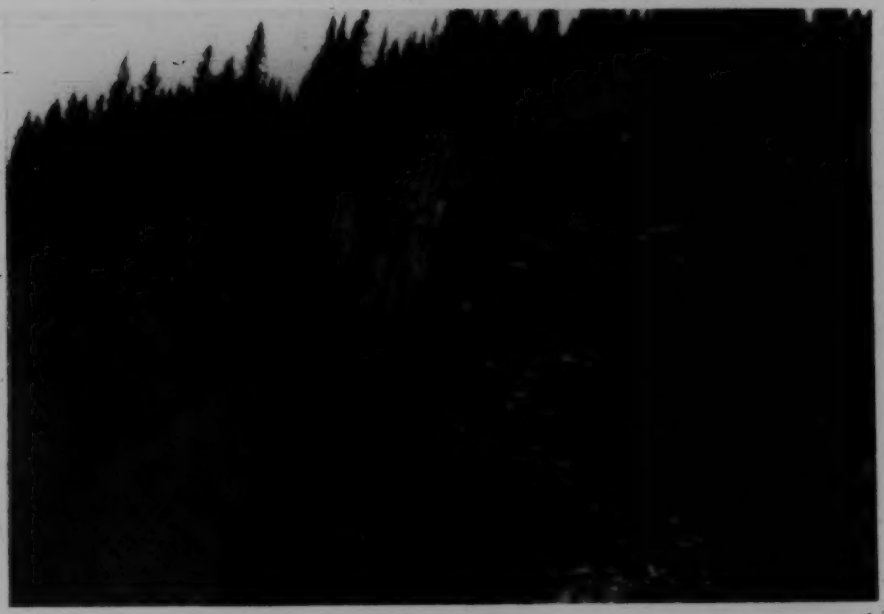

The topple is in the Spray River Formation and the dashed lines separate different toppled blocks.

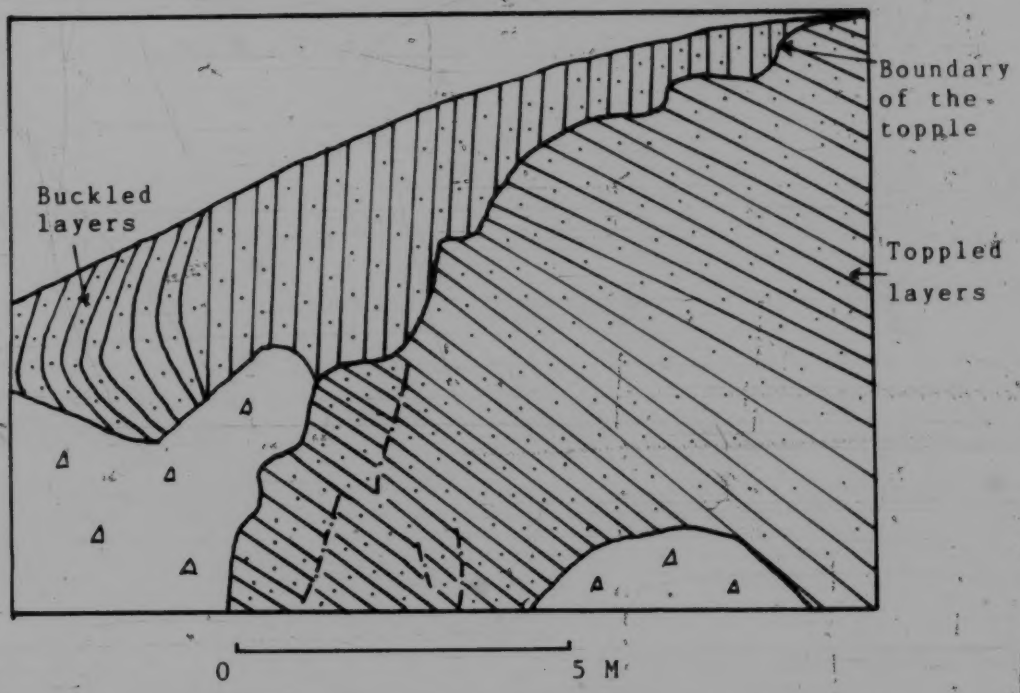
Figure 3.7 Toppling at the toe of Site #2

creek to the top of the toppled rock masses perpendicular to the bottom of the creek is larger than 15 metres. The rocks at the toe of the slope are sandstones with bedding thicknesses of 30 cm to 50 cm. The joint spacings are 50 cm to 1 m and the mode of the h/b is 1 to 2. The rock below the thickly bedded sandstones is thin to medium bedded sandstones with thin shale layers. The average bedding thickness is less than 4 cm and the h/b is 3-5 for sandstones. The toppling deformation at this site is controlled by thick layers. The uniaxial compressive strengths of the thickly bedded sandstones are over 200 MPa and those of the thinner layers below the thick beds are about 80 MPa. The slope angle is about 50° at the toe of the slope and becomes less upwards on the slope.

### 3.3.3 Site #3

The site is located on the south side of Creek 1 (Figs. 3.1 and 3.4). The toppled layers here have rotated over 60-70° (Fig. 3.8). The topple is like a chevron fold although the undeformed layers are covered by debris in Fig. 3.8. The interlimb angle is 110° to 120°. Steeply dipping (60°) cracks develop in the rock mass mainly following the strike joints. The thickness of the toppled rock mass perpendicular to the slope surface is about 3 m and its length along the slope is 10 m. The dip angle of the hinge surface is about 40°. The attitude of the rotated bedding surfaces is at 40°/040° and the untoppled layers are at






—·—·— Steep cracks mainly following strike joints.

The topple is in the Spray River Formation.

Figure 3.8 Toppling at Site #3

80°/249°. The rocks are medium to thinly bedded sandstones. The bedding thickness is 1-12 cm with the mode of about 5 cm. The average h/b is 3-4. The uniaxial compressive strength is 80 MPa for sandstone blocks. The slope angle is 50° to 60°.

The layers on the other side of Creek 1 have buckled besides toppling (Fig. 3.8).

### 3.3.4 Site #4

The site is located on the south side of Creek 1 in the sandstones towards the base of the Spray River Group (Figs. 3.1 and 3.4). A hinge surface dipping to the SW at up to 15° (Fig. 3.9) is the result of toppling. The toppled layers form smooth curves without any sharp changes of dip angles of the layers. The layers rotated more around the toe of topple than elsewhere. The toppled rock mass is 1.5 m thick by 5 m long in the cross section. Joints were opened by toppling, particularly around the toe of the topple. The slope angle is about 32° except at the toe of the topple. The rocks are thin to medium bedded, light brown, weathering, fine grained sandstones. The untoppled layers are at 76°/226°. The toppled layers dip at 0° to 50°. The bedding thickness is 1-5 cm with a mode of 2 cm. The h/b is 1 to 2 around the toe of the topple and 2 to 5 on the other parts.

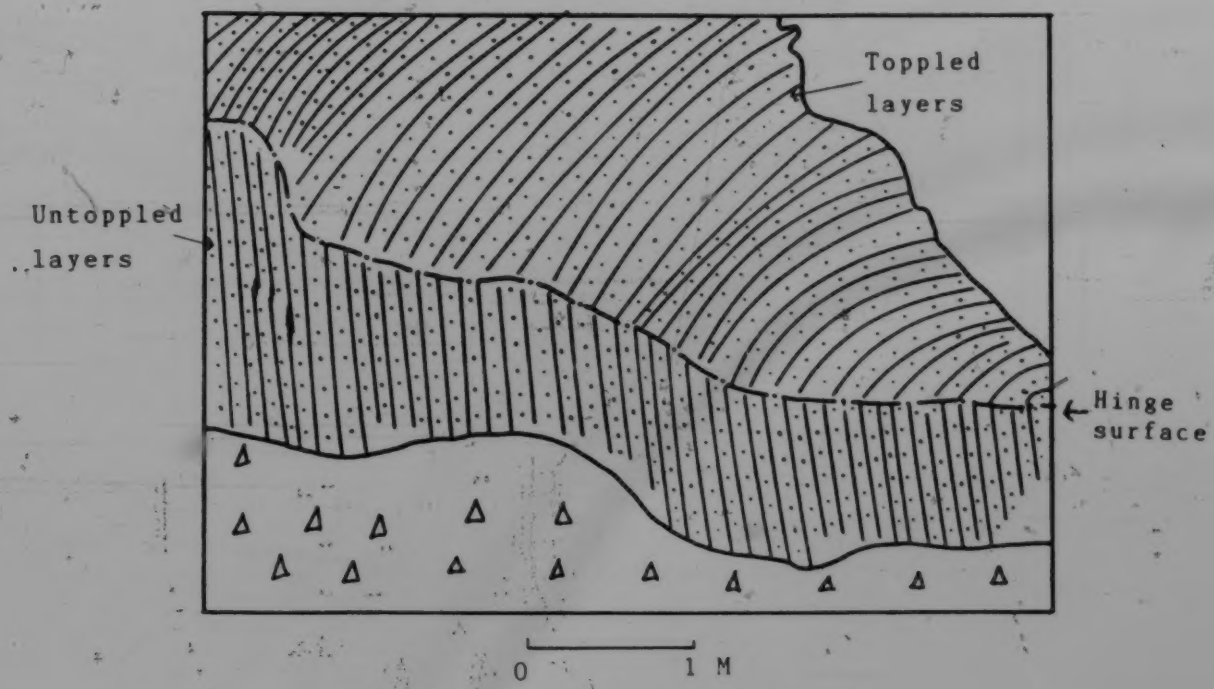



Figure 3.9 Toppling at Site #4

### 3.3.5 Site #5

The site is located on the south side of Creek 3 and the topple is low in the sandstones (Figs. 3.1 and 3.4). The layers form a chevron-like topple (Fig. 3.10). The rupture surface is close to the hinge surface dipping at 35° and there are also steep cracks at 55 to 60°. The rupture surface is covered by debris and the length of the planar part is less than 10 m. Rock masses above the hinge surfaces have been displaced. The rock layers along the hinge or rupture surface were broken or cut across layers. Around the rupture surface, rock layers were smashed to small pieces due to rotation and probably sliding of toppled rock masses. The rocks are thinly to medium bedded, light brown to yellow weathering, fine grained sandstones. The untoppled bedding orientation is 80°/226° and the toppled layers are at 30-40°/060°. The thickness of the bedding is 0.5-25 cm with the mode of 1.5 cm. The layers are easy to break into thinner layers. The joint spacing is 7-15 cm with the mode of 10 cm. The average h/b is 6.5. The uniaxial compressive strength is about 80 MPa. The ground surface slopes at about 35°.

### 3.3.6 Site #6

This site is located on the south side of Creek 3 and the site is in the thin to medium bedded sandstones (Figs. 3.1 and 3.4). There is a well developed hinge surface dipping at 30° (Fig. 3.11). Most of the toppled layers are

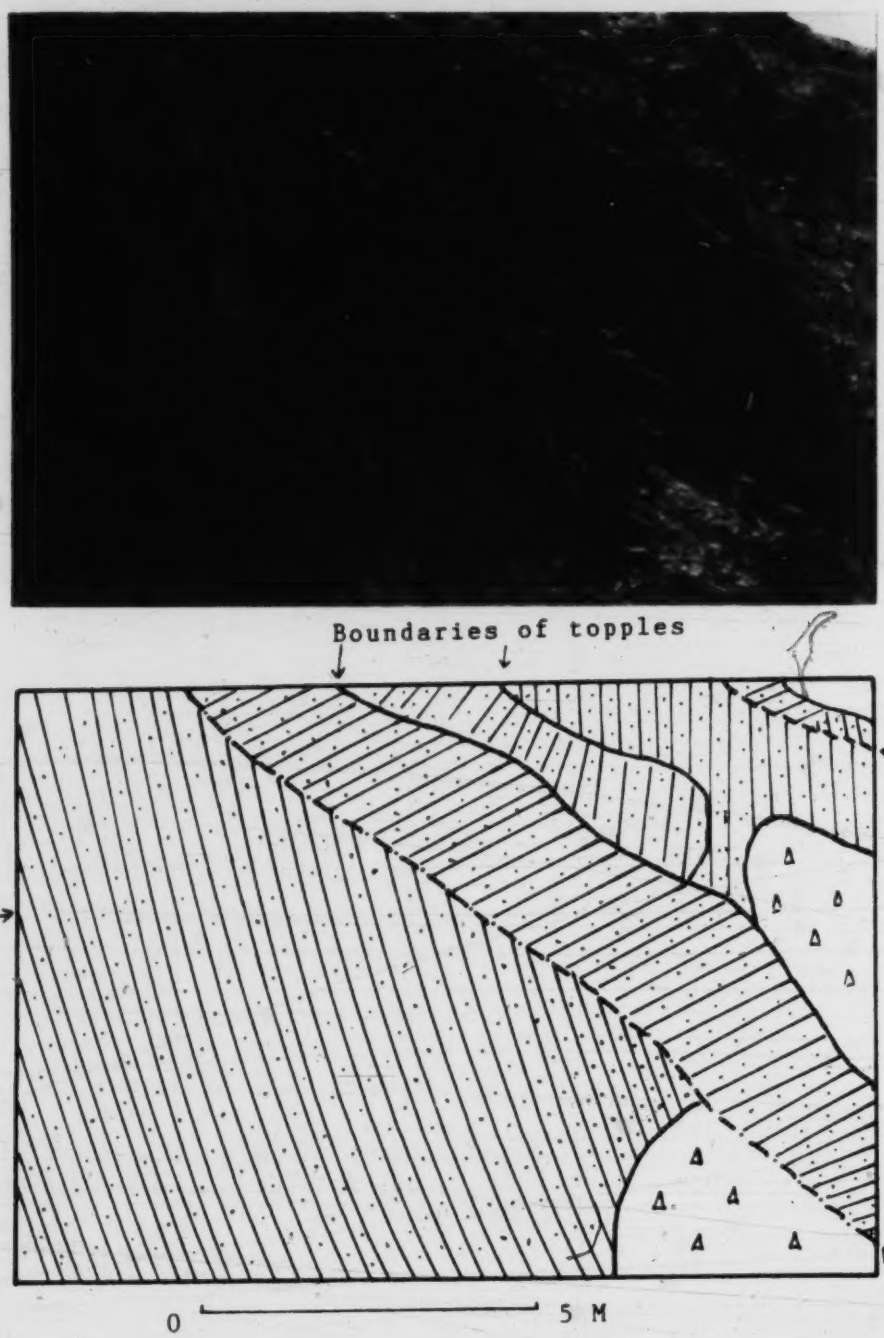



Figure 3.10 Toppling at Site #5

more or less parallel to each other. The topple is like a chevron fold. There are some folded layers around the topple (Fig. 3.11), which may indicate that the layers were deformed before the topple developed. The hinge surface may follow the hinge surface of a fold formed before toppling. Some cracks formed following the strike joints around the toe. The toppled rock layers change from 73-83°/224° to 30°-50°/050°. The bedding thickness is 2 to 10 cm with a mode of 4 cm. The joint spacing is 5-40 cm with a mode of 15 cm. The h/b is 2-3. There are some openings of the strike joints and displacement along them in the toppled rock mass due to toppling but no shear displacement along the hinge surface is seen. The slope angle is 30° to 40° except around the toe where the slope is at about 60°.

### 3.3.7 Site #7

The site is located in the 4th creek (Figs. 3.1 and 3.4). The topple is on both sides of the creek and in the thin to medium bedded sandstones. There is a sliding surface in the topple (Fig. 3.12) and along the sliding surface, the rock blocks rotated more than the adjacent blocks of the same layer. The blocks at the sliding surface are square in cross section. The rotation of the rock blocks on the sliding surface indicate a small sliding displacement along the surface. There is a buckle above the top of the toppled rock mass and buckled rock masses may have pushed the toppled layers and assisted formation of the sliding

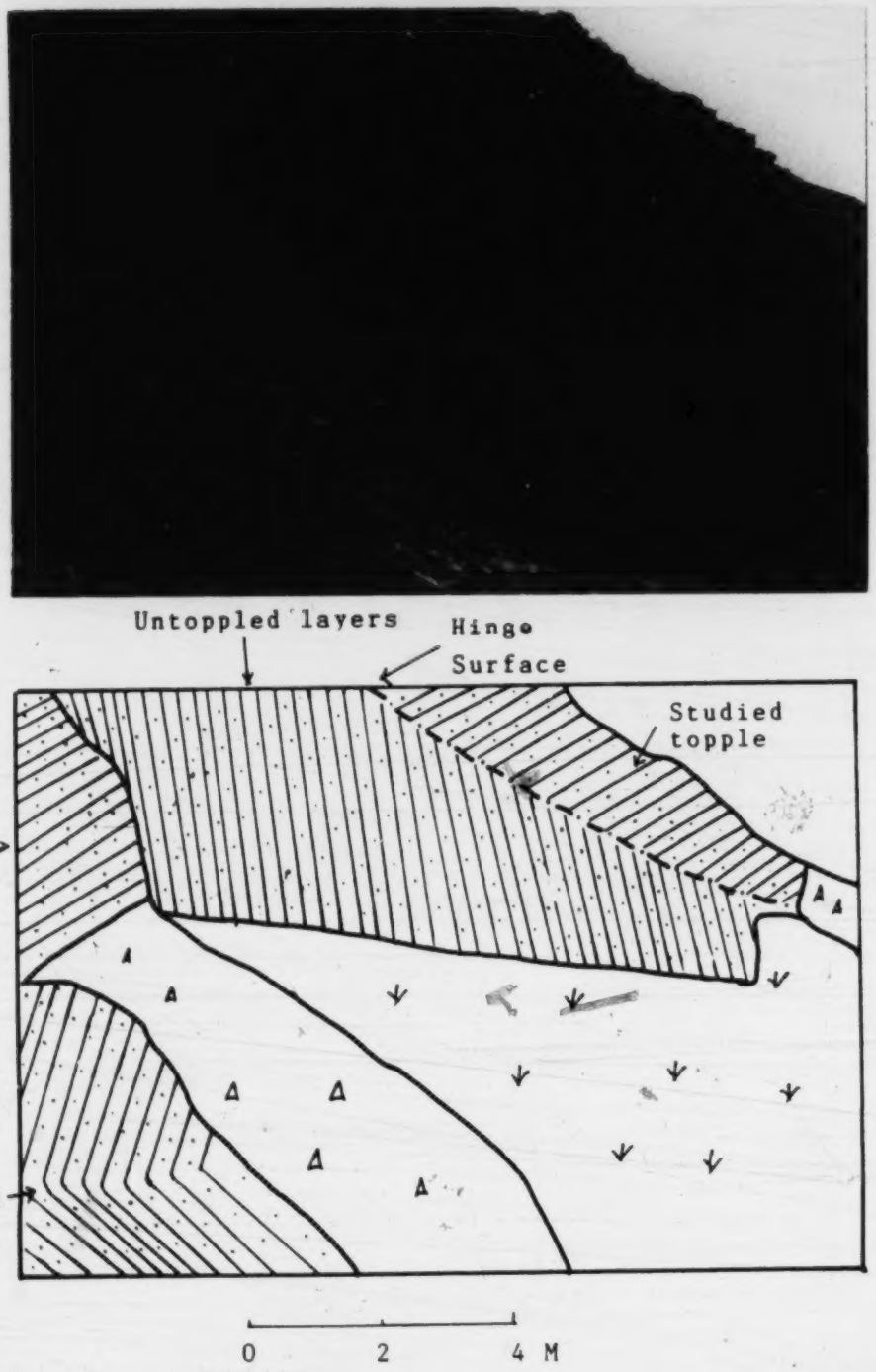



Figure 3.11 Toppling at Site #6

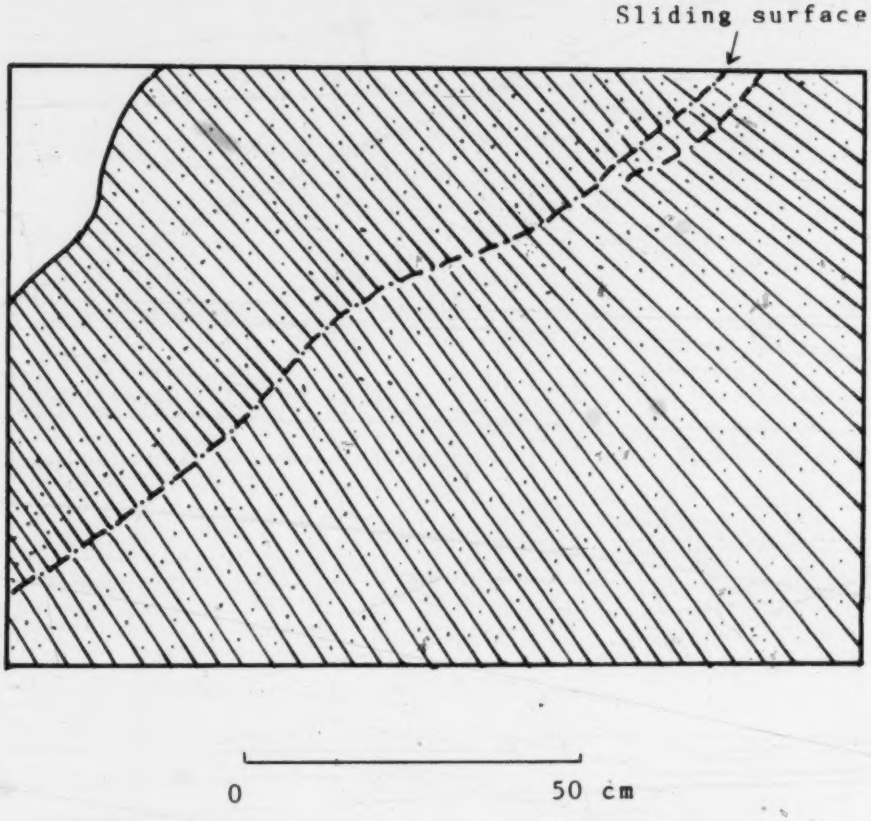
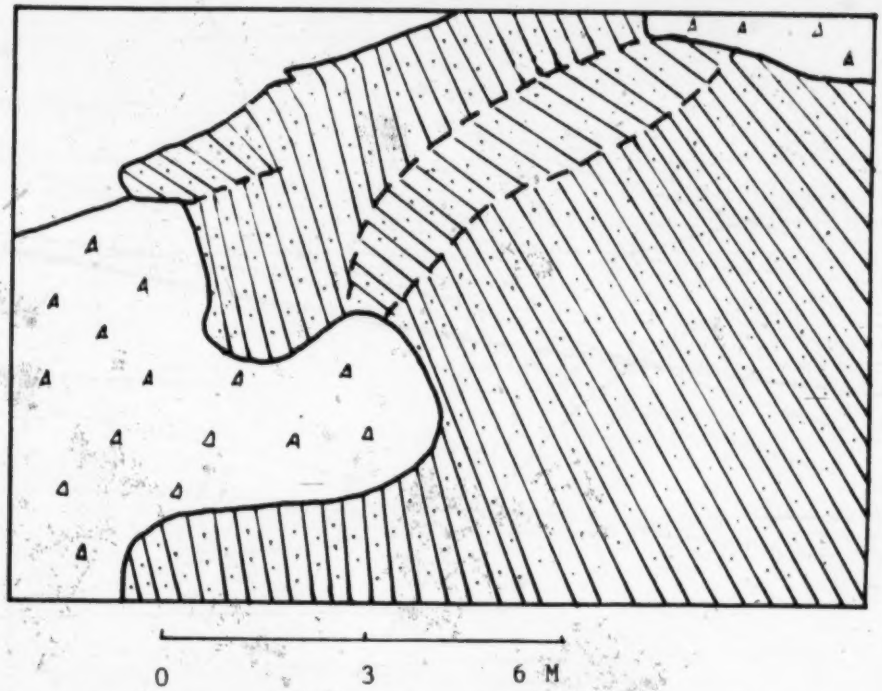



Figure 3.12 Sliding surface at Site #7

surface. The buckle is described as buckle 3 in chapter 4. The thickness of the toppled rock mass above the sliding surface perpendicular to the sliding surface is less than 5 metres. The toppled bedding surfaces are at 49°/060°. The untoppled bedding structure can not be seen on the surface. The bedding thickness is 4-11 cm with a mode of 5 cm and the joint spacing is 6-26 cm with a mode of 8 to 10 cm. The average h/b is about 1.5 to 2. The rocks are thin to medium bedded, light-brown to buff weathering, fine-grained sandstones.The uniaxial compressive strength is 80 to 200 MPa. The slope angle is 75° for the part with toppled rock layers around the toe of the slope.

### 3.3.8 Site #8

The site is just above site #7 on the ridge north of creek 4 (Fig. 3.1) and the toppled layers change their dip angles several times (Fig. 3.13). There are several toppled blocks. The orientations of bedding surfaces change from 53°/090° to 30°/112° at the ground surface. The strike changes of the layers are probably due to rotation caused by gully formation. The thickness of the toppled rock mass perpendicular to the slope is less than 5 metres. The rock layers are laminae of thin to medium bedded sandstones and shales. The bedding thickness is 1-5 cm with the mode of 2.5 cm and the joint spacing is 10-20 cm with the mode of 12 cm. The average h/b is 3-4. The slope angle is about 40°.




Dashed lines separate different toppled blocks.

Figure 3.13 Toppling at Site #8

### 3.3.9 Site #9

The site is located on the south side of the 5th creek. The site is around the boundary of the shales and the sandstones (Figs. 3.2 and 3.4). There are several sliding surfaces, the least steep one is at 32° (Fig. 3.14). The length of the planar part of the sliding surfaces is about 10 metres. The sliding surfaces are oblique to both the bedding planes and the strike joints. The rocks are thinly to medium bedded, brown-buff weathering, fine grained sandstones. The rock layers rotated from steep southwest dips to 34°/040°. The untoppled rock masses can be seen only around the bottom of the creek. The thickness of the toppled rock mass perpendicular to the bottom of the creek is at least 10 metres. The thickness of the bedding is 1-4 cm with the mode of 1.5 cm and the joint spacings are 3-14 cm. The average h/b is 5. The uniaxial compressive strength is estimated as 50 MPa to 80 MPa. The slope angle is about 30°.

### 3.3.10 Site #10

This site is on the ridge of the Rock Glacier between the 8th and the 9th creeks (Fig. 3.2). The rock layers toppled in different ways at different locations along the slope.

The lower part of the slope is covered by debris of the Rock Glacier. The site is the lower half of the slope.

The thickly bedded sandstones (Fig. 3.15) are toppled, which can be seen in the 8th creek and the toppled layers

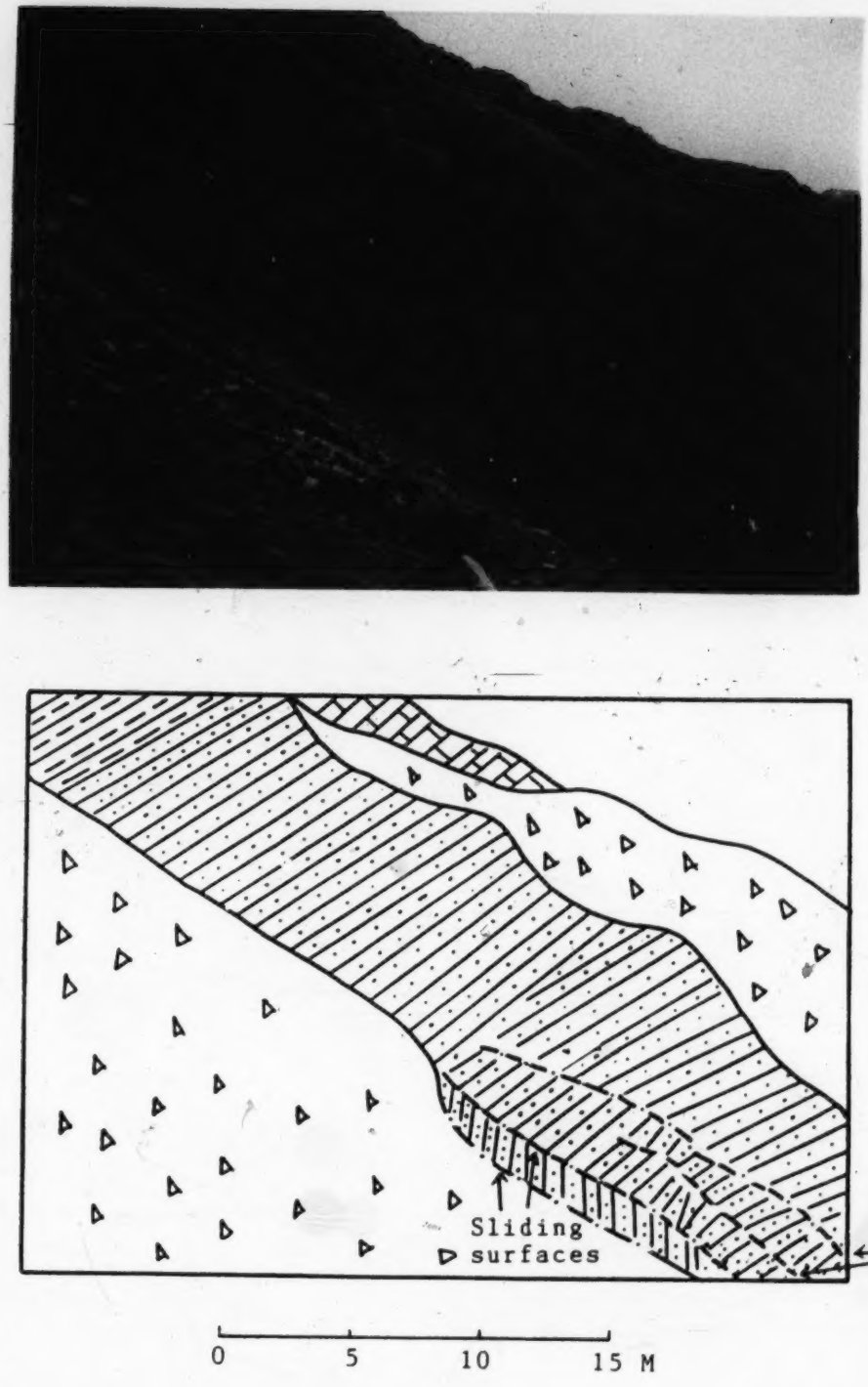



Figure 3.14 Toppling at Site #9

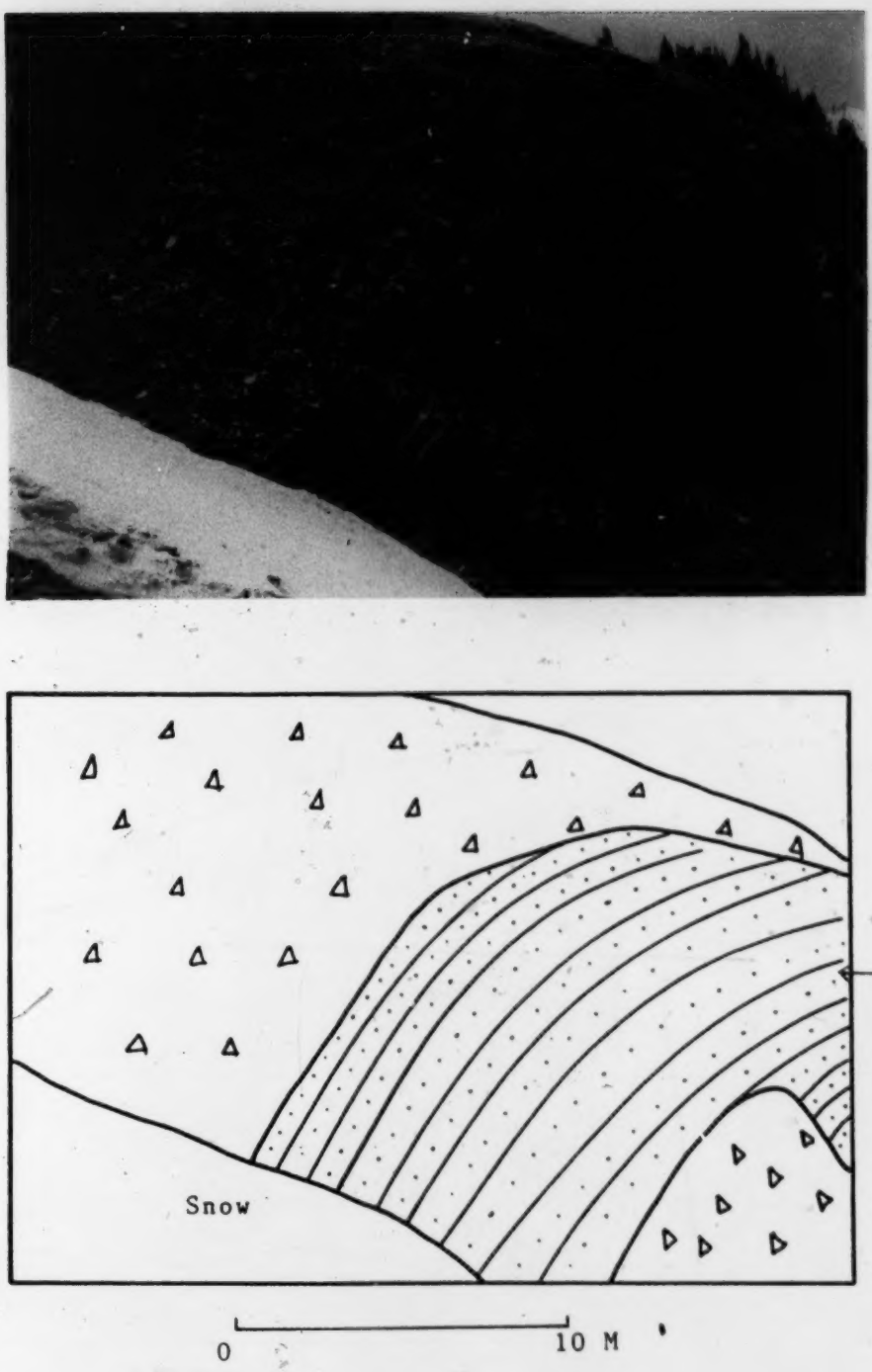


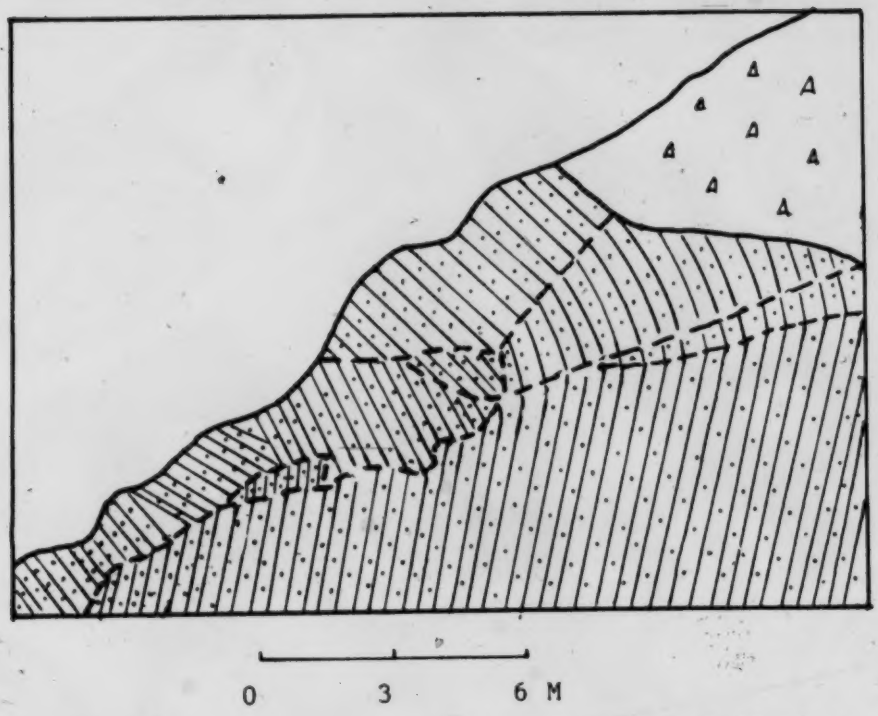

Figure 3.15 Toppling at Site #10

are generally at 55°-60°/062°-080°. The toppled layers form smooth curves without any abrupt changes of orientations of bedding planes. This topple is at least 15 metres thick. But around the surface of the slope, the dip angle can be as low as 25°. The bedding thickness is 30-100 cm. The h/b is not more than 3 with a mode of 2. The slope angle is 25°.

### 3.3.11 Site #11

The site is the upper part of the slope above the Rock Glacier (Fig. 3.2). On the south side of the site, where the toppled rock masses are supported by a strong rockwall around the toe of the topple, there is a hinge surface dipping at 20-25° and there are several toppled blocks (Fig. 3.16). The layers rotated 50-60°. Just 5 metres north of the south end of the rockwall, where the rockwall is eroded away, there is a sliding surface dipping at 37°. Around the sliding surface, some of the blocks have rotated more than 30° compared with the blocks along the same layers. The bedding thicknesses are 10 to 30 cm and h/b varies from 2 to 5 depending on bedding thicknesses. Slope angle is 30°.

On the middle of the ridge where the thick bedded rockwall is eroded away, the toppled rock layers are thin to medium bedded sandstones. The layers rotated to dip NE at 20-30° and steep cracks (60°) develop (Fig. 3.17). The thickness of the toppled rock masses perpendicular to the slope surface is about 3 metres. The bedding thickness is 0.5 to 3 cm with the mode of 2 cm and the joint spacings are




Dashed lines separate different toppled blocks.

Figure 3.16 Toppling on the south side of Site #11

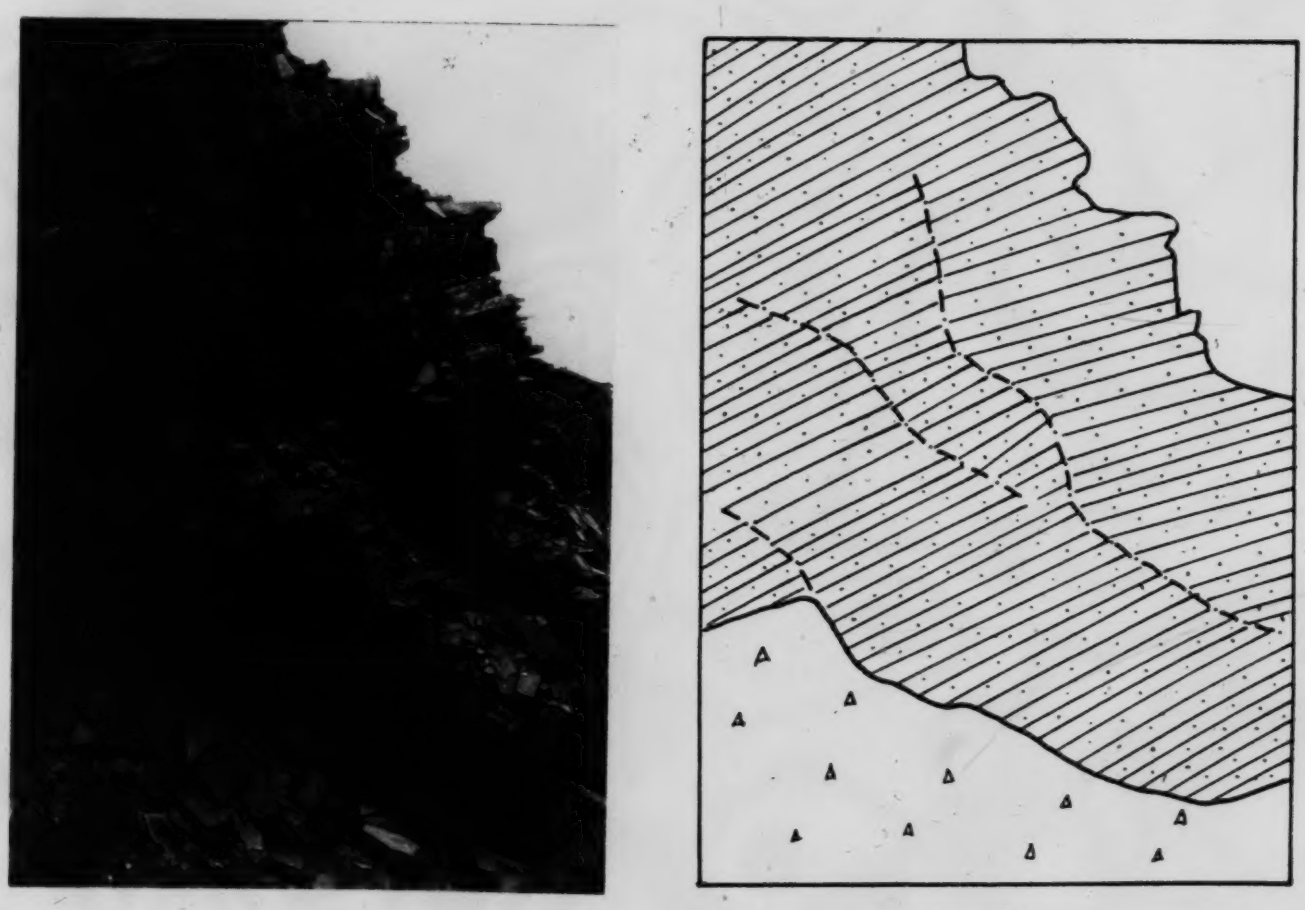



Fig. 3.17. Toppling in the middle of the ridge at Site #11. The dashed lines are steep cracks.

5-30 cm with the mode of 10 cm. The average h/b is 5. The slope angle is 40-50°.

### 3.3.12 Site #12

The site is located on the south side of the 9th creek (Fig. 3.2). The site is in the sandstones next to the shales in the Rocky Mountain Group (Fig. 3.4). Here a sliding surface develop at 38° (Fig. 3.18) and rock masses above sliding surface have been displaced. The length of the planar part of the sliding surface is less than 20 metres. There are other planar surfaces which are at most 5° steeper than the sliding surface but shorter too and these surfaces may also form as the results of sliding of rock masses above them. The sliding surface is oblique to both the bedding layers and strike joints. The maximum thickness of toppled rock masses perpendicular to the sliding surface is larger than 10 metres. The toppled beds are at 21-30°/060°. The bedding thickness is 1 to 5 cm with the mode of 2 cm and the joint spacings are 5 to 20 cm with the mode of 10 cm. The average h/b is 4. The slope angle is 30 to 35°.

### 3.3.13 Sites #13-#14

The sites are located north of the Highwood Pass and south of the Rock Glacier. Site #13 is north of Creek 10 and Site #14 is south of Site #13 across Creek 10 (Fig. 3.3). Debris of 5 to 10 centimetres thick covers both the slopes. At both the sites, the toppled rock layers dip NE at 20-70°

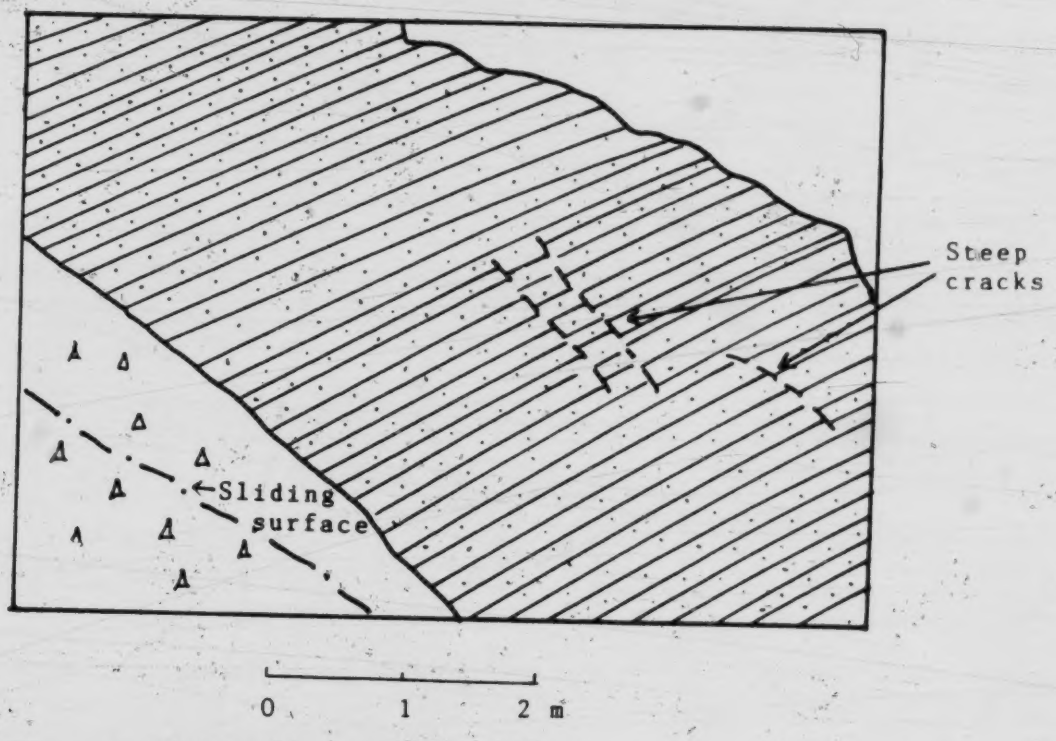



Figure 3.18 Toppling at Site #12

but the untoppled rock layers dip to SW. Most of the toppled layers are at about 70°/060° except that small portion of the toppled blocks on ground surfaces rotated more and at 30°-40°/60°. The thickness of the toppled rock mass perpendicular to the slope surface is less than 5 metres at both sites. In the bottom of Creek 10 between the two sites, the layers are not toppled. There is a potential sliding surface along the bottom of the gully and the blocks in this zone are at 35°/060°. (Fig. 3.19). The orientation of the layers change across the potential sliding surface and the layers have been deformed to form curves, which may indicate slow downslope movement (Fig. 3.20). The slope angle is 35° and the dip angle of the potential sliding surface is also 35°. The bedding surfaces of the toppled rock layers are 20°-70°/057°-060°. The thickness of the bedding is about 5 cm for the sandstones. Some of the thick layers are as thick as 30 cm and the shale layers in between are as thin as 5 mm. The joint spacing of the strike joints is 5-60 cm with the mode of 10-20 cm. The average h/b is 3-4.

### 3.3.14 Site #15

The site is above Site #14 on the same slope (Fig. 3.3). There is a sliding surface in the topple and the planar part of the sliding surface is less than 10 metres. The layers around the hinge surface between the toppled and untoppled rock mass are deformed to form curves, which may indicate slow downslope movement. There are also some steep

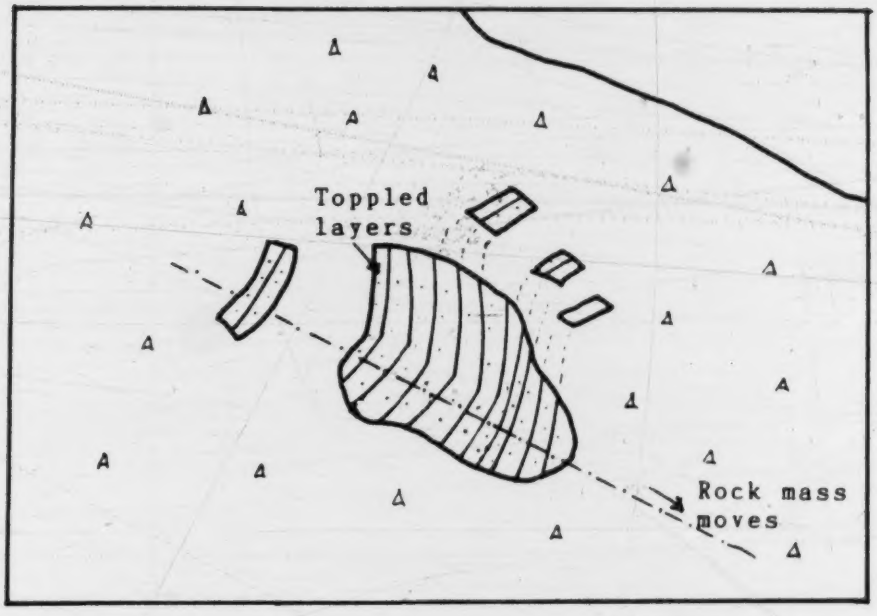
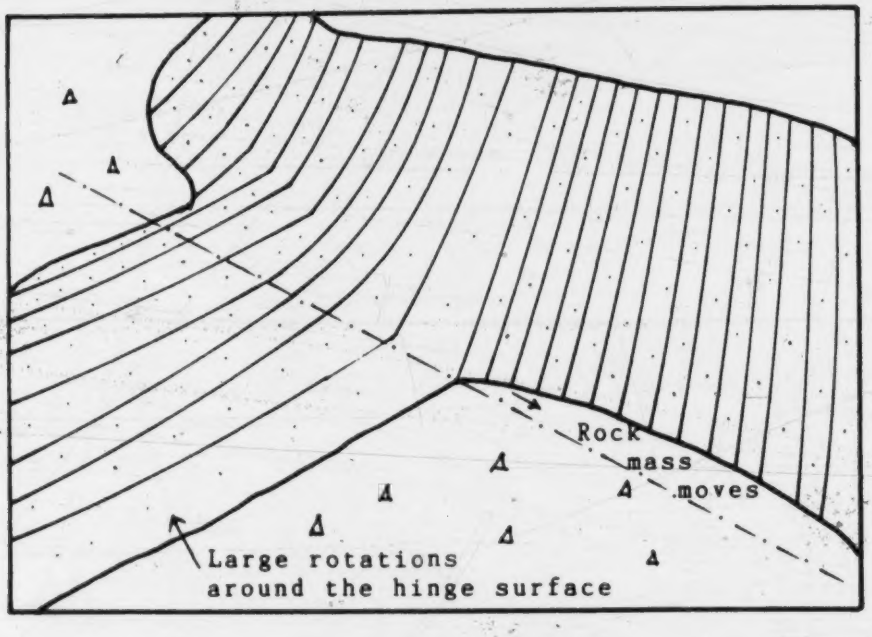



Figure 3.19 Toppling at Site #14




0 1 2 m

Figure 3.20 Rotation of layers around the bottom of the creek at Site #14

discontinuitie (steep cracks) following the joint sets in the toppled rock layers.

The rocks are thin to medium bedded, buff to dark brown weathering, fine grained calcareous sandstones. The uniaxial compressive strength is estimated as 200 MPa. The bedding orientations of the toppled layers are 10°-50°/040°-050° for the toppled layers. The bedding thickness is 1-5 cm with a mode of 2 cm. The joint spacing is 5-25 cm with a mode of 10 cm. So the average h/b is 5. The slope angle is 35°.

### 3.3.15 Site #16

The site is located north of the 12th creek and the site is in the lower sandstones. (Figs. 3.1 and 3.4). The topples are generally less than 2 m thick perpendicular to the slope surfaces (Fig. 3.21). There are well developed hinge surfaces and the dip angles of these hinge surfaces are generally less than 15°. There are several toppled blocks. The toppled rock layers are at 10° to 50° dipping to 060°. The rocks are thin to medium bedded, brown, fine grained sandstones. The thickness of the bedding is 1-2 cm and the joint spacing is 20-30 cm. The average h/b is larger than 10. There are some short sliding surfaces ( less than 5 m) where the h/b is noticeably smaller ( 3-4 ). The dip angle of these small planar structures is about 32°. The uniaxial compressive strength is 80 MPa. The slope angle is 25°.

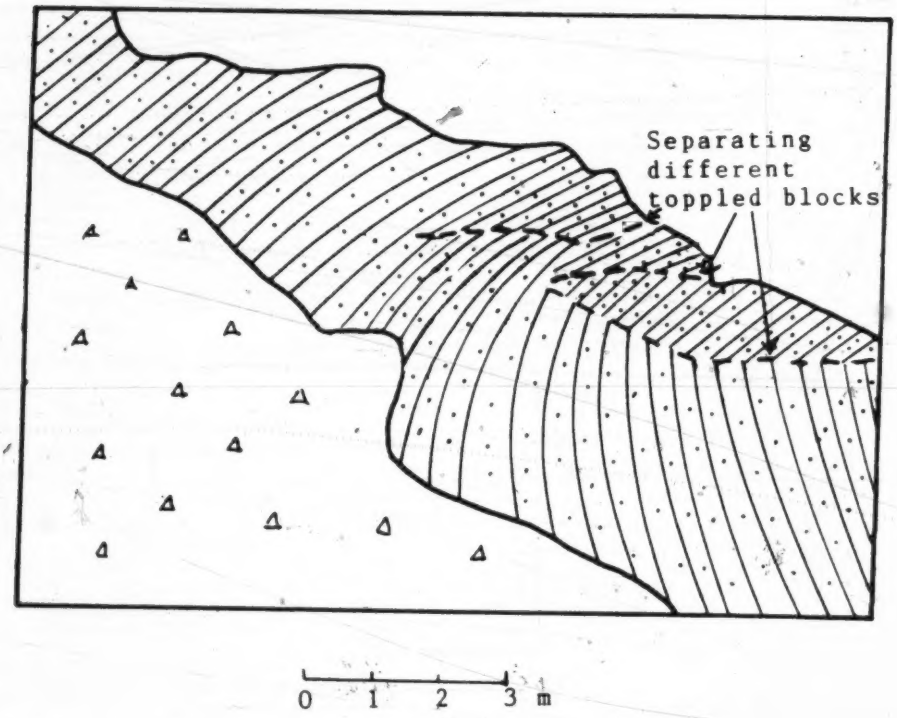



Figure 3.21 Toppling at Site #16

### 3.4 Deformation styles of topples

Goodman and Bray (1976) suggested three classes of topples, the flexures of columns with no pre-existing cross-fractures, the toppling of blocks bounded by widely-spaced kathetal fractures and block flexure topples for columns containing numerous cross-fractures. This classification is based on the fractures perpendicular to penetrative discontinuities and the response of block systems to toppling processes.

Although rock blocks in topples on underdip slopes generally rotate more than those in topples on anaclinal slopes, the classification of Goodman and Bray (1976) can still be used for topples on underdip slopes. Layers in flexure topples and block flexure topples show smooth curves and bedding orientations gradually change along bedding layers. In block topples, a few blocks move together as an intact block and bedding orientations generally change abruptly.

In the Highwood Pass area, the rock layers always have cross fractures, so there are only block topples and block flexure topples. To differentiate between block topples and block flexture topples in the field, I suggest that, if the change of dips between adjacent blocks along bedding layers is less than 10°, the topple is considered as a block flexure topple, and otherwise the topple is a block topple. In the field, bedding dips change less than 10° from one block to next along a layer in block flexure topples.

Some toppled bedding layers change dips several times and the change is more than 10° each time. There are several "intact" blocks in a topple and in each "intact" block, bedding orientations of the layers are the same. All this suggests that there was more than one episode of toppling in these topples. I call these topples in the Highwood Pass, complex, multiple block topples in contrast to the simple single block topples sketched by Goodman and Bray (1976).

As layers in the topples on underdip slopes in Highwood Pass are rotated from dipping SW to dipping NE, there are always hinge zones where the bedding planes show the largest change in dip angles. At some sites, the topples are like chevron folds. The dip angles of the two limbs of the topple are almost constant and change of dip angle is concentrated in the hinge zone. In this case, I call the topples chevron topples by analogy with chevron folds (Ramsay and Huber, 1987, p.442).

Fig. 3.22 shows idealized shapes of three different types of topples. Blocks in block flexure topples gradually change orientations along bedding layers everywhere but there is generally more than one abrupt change of block orientations along bedding layers in complex multiple block topples. In chevron topples, toppled rock layers have more or less constant orientations.

Responses of rock block systems to toppling processes are determined by several factors including block sizes, original discontinuity orientations, strengths of rock

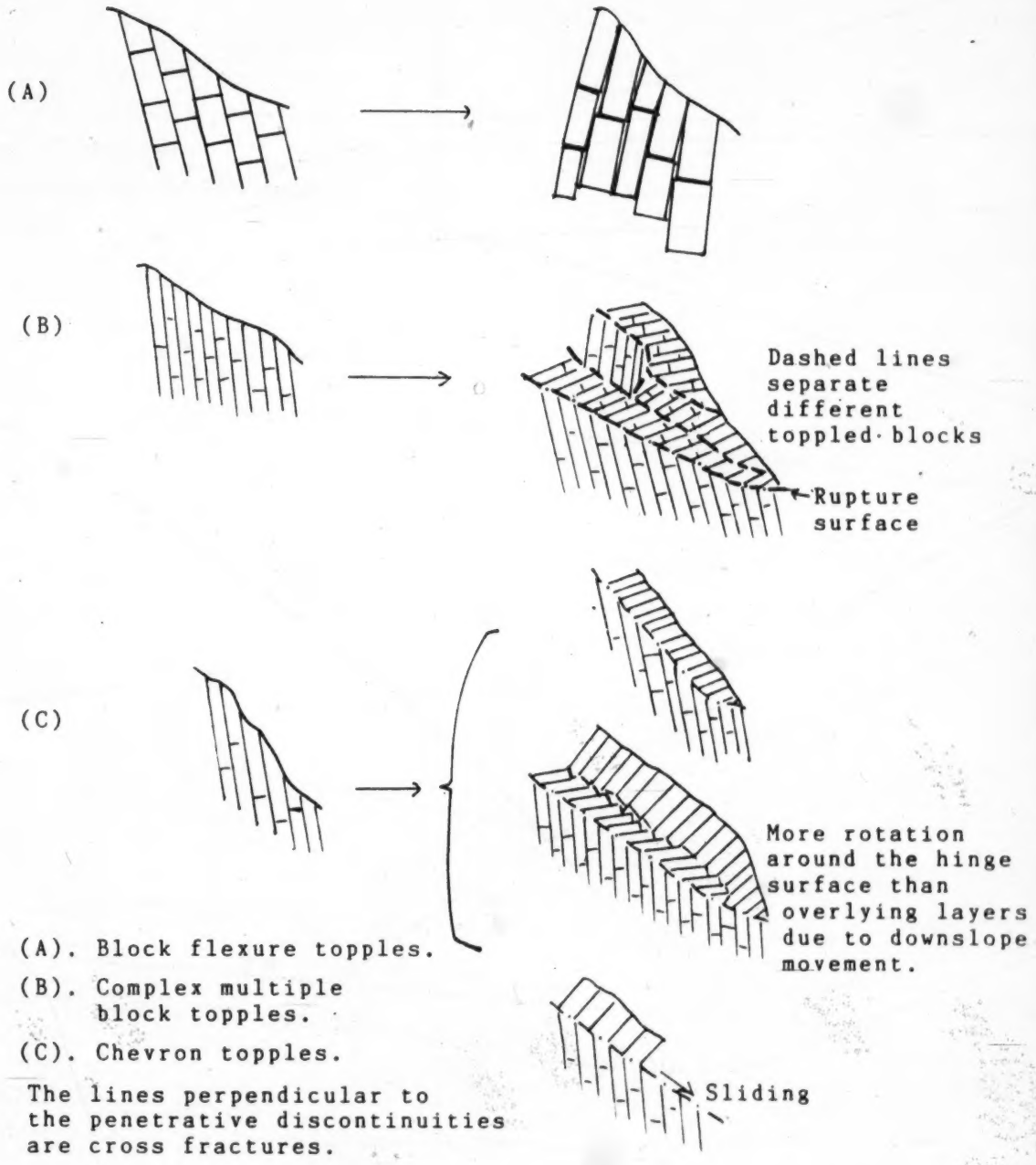
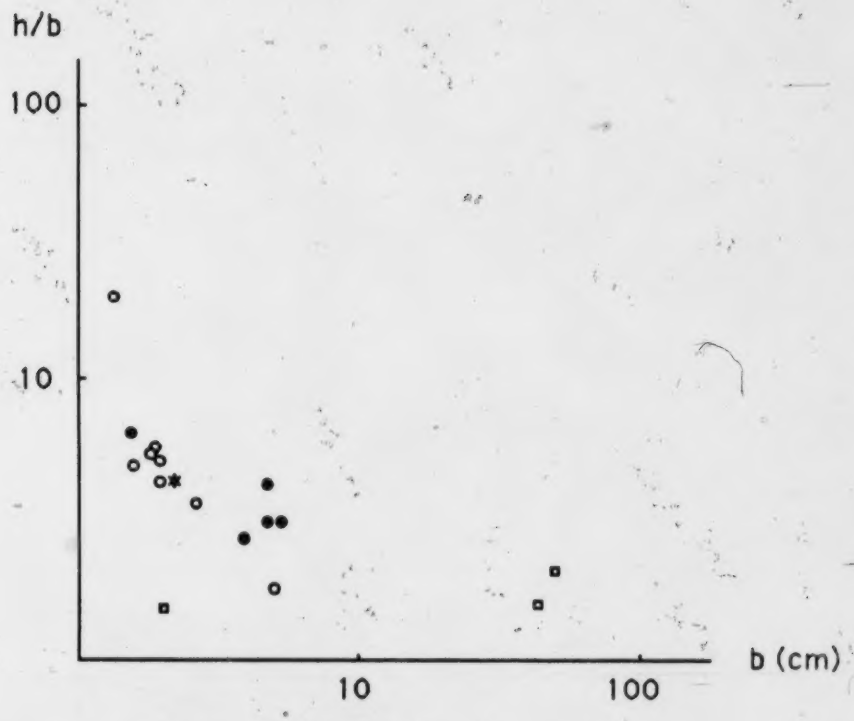

(A)
(B)
Dashed lines separate different toppled blocks
Rupture surface
(C)
More rotation around the hinge surface than overlying layers due to downslope movement.
(A). Block flexure topples.
(B). Complex multiple block topples.
(C). Chevron topples.
The lines perpendicular to the penetrative discontinuities are cross fractures.
Sliding

Figure 3.22 Idealized shapes of different types of topples

blocks and external forces. The original discontinuity orientations are similar at all these sites. The external forces may include water pressures in discontinuities and pressures from freezing processes and the weight of the overlying ice of ancient glaciers (Tang, 1986). In the analysis here, I assume that effects from external forces are not noticeably different at all the sites because these sites are close together. The strengths of rock blocks are found to be related to discontinuity spacings, i.e. the thicker the beds, the stronger the blocks, so the influences of block structures and strengths of blocks can be considered as only one variable. So only the relationship between rock structures and deformation styles is discussed here.

The block flexure topples (Sites 2, 4 and 10) are found where h/b lies between 1 and 2 (Fig. 3.23). Scales of the block flexure topples are dependent on block sizes, and on bedding thicknesses. For instance, the topple at Site #10 is larger than that at Site #4 because of the larger block sizes at Site #10 than those at Site #4. Blocks may rotate more around the toe of a topple than in the upper part and h/b may be smaller around the toe than elsewhere, e.g at Site #4. This suggests that toes of a block flexure topple may develop where rock blocks have small h/b. Blocks bounded by bedding planes and strike joints are gradually rotated and joints are opened by this process.




▫ Block flexure topples.

○ Complex, multiple block topples.

● Chevron topples.

h/b Ratio of joint spacing to bedding thickness.

b Bedding thickness.

* Middle of the ridge at Site #11.

Figure 3.23 Relationship between ratios of joint spacings to bedding thicknesses and bedding thicknesses for different topples

Block topples and complex multiple-block topples (Sites 1, 7, 8, 9, 11,12, 15 and 16) are found where bedding thicknesses are less than 30 cm and block ratios (h/b) are larger than 2. The only exception is Site #7 where h/b is less than 2. The topple at Site #7 may be assisted by buckling of the rocks above. A few layers are combined together when the rock masses are toppled. These intact blocks can be separated from other parts of the rock masses by sliding along sliding surfaces at the later stages of toppling. Bedding orientations may change several times along a layer in a complex multiple block topple, particularly when bedding layers are thinner than 5 cm.

In chevron topples (Sites 3, 5, 6, 13 and 14) most of the toppled rock layers have more or less the same orientations except that rock blocks on ground surfaces may rotate more. Bedding thickness and h/b are the same as those in block topples. The toppled rock masses also form blocks which can be displaced later as at Site #5. The interlimb angles range from 100° (Site #6) to 150° (Sites #13 and #14). Hinge surfaces may become sliding surfaces later.

### 3.5 Discontinuities formed during toppling processes

Hinge surfaces, rupture surfaces, sliding surfaces and steep cracks are common features formed during toppling processes. Rock masses can be displaced along these surfaces to form slides or falls. Table 3.1 gives a summary of hinge surfaces, sliding surfaces and steep cracks at all the study

sites. Rupture surfaces are the surfaces separating toppled and untoppled rock masses. Sliding surfaces are planar structures along which rock masses have been displaced a short distance (Fig. 3.12) or rock masses have slid leaving only planar surfaces (Fig. 3.14).

Hinge surfaces are clearly seen at most of the sites except for some block flexure topples where the hinge surfaces are not exposed on the ground surfaces. Hinge surfaces join hinge lines on each layer and hinge lines are where the rate of change of orientation of the layer reaches a maximum.

Block flexure topples change bedding orientations gradually like folds. Hinge surfaces are above rupture surfaces separating toppled and untoppled layers or coincide with rupture surfaces.

In block, complex multiple block and chevron topples, hinge surfaces separate toppled and untoppled layers. There are always abrupt changes of dip direction around hinge surfaces. Besides hinge surfaces separating toppled layers from untoppled layers, there are also other hinge surfaces across which bedding dips change abruptly in a complex multiple-block topple, e.g. dip changes around the toe of the topple in Fig. 3.14. In chevron topples, hinge surfaces separate toppled and untoppled rock masses and dips of toppled layers are almost constant (e.g. Figs. 3.10 and 3.11) except where toppled layers have not rotated large angles and some individual blocks close to the ground

Table 3.1 Discontinuities formed by toppling at all the toppling sites

| Sites | Deformation Styles | Hinge Surfaces | Sliding Surfaces | Steep Cracks |
|---|---|---|---|---|
| 1 | B | YES | YES | YES |
| 2 | BF | Not seen | NO | NO |
| 3 | C | YES | NO | YES |
| 4 | BF | YES | NO | NO |
| 5 | C | YES | YES | NO |
| 6 | C | YES | NO | YES |
| 7 | B | Not seen | YES | NO |
| 8 | B | Not seen | NO | NO |
| 9 | B | YES | YES | NO |
| 10 | BF | Not seen | NO | NO |
| 11 | B | YES | YES | YES |
| 12 | B | Not seen | YES | YES |
| 13 | C | YES | YES(?) | NO |
| 14 | C | YES | YES(?) | NO |
| 15 | B | YES | YES(?) | NO |
| 16 | B | YES | YES | NO |

B: Block topples or complex, multiple block topples.
BF: Block flexure topples.
C: Chevron topples.
?: Possible.

surface have rotated further (e.g., Fig. 3.19).

Dip angles of hinge surfaces are less than 15° for block flexure topples (Site #4). Dip angles of hinge surfaces vary but are less than 25° for complex multiple block topples depending on discontinuity spacings. Smaller bedding thicknesses are associated with smaller dip angles of hinge surfaces. For example, the hinge surface at Site #16 is almost horizontal for the bedding thickness of 1 to 3 cm. But the hinge surface at the south part of Site #11 is 20-25° where the bedding thickness is 20 cm for some layers. Dip angles of hinge surfaces are 30° to 60° for chevron topples and they are more or less parallel to slope surfaces.

Sliding surfaces develop well in the thin bedded sandstones where the h/b is larger than 3 and the average bedding thickness is 1.5 cm to 2 cm with some thinner layers. The sliding surfaces may partly follow the joints and partly cut thin rock layers (Sites #5 and #9). But overall orientations of sliding surfaces are oblique to both bedding surfaces and strike joints. Sliding surfaces are planar and usually less than 10 metres long. The dip angles of the sliding surfaces are larger than 32°.

Sliding surfaces also develop where bedding thicknesses are larger and shearing through rock blocks is not possible. The rock blocks along the sliding surfaces have rotated large angles compared with the adjacent blocks along the same rock layers. The rotations of rock blocks along the

sliding surfaces are due to movement of the rock mass above as an intact rock block (Site #7). Dip angles of sliding surfaces are around 40° which is a little higher than basic friction angles of these rocks. Overcoming roughness from interlocking of blocks to form sliding surfaces may result in higher dip angles than basic friction angles.

In some chevron topples, sliding surfaces may follow hinge surfaces when they dip at less than 40° (Site #5). In some chevron topples, layers are deformed to form curves due to small displacements of rock masses above hinge surfaces (Site #14).

Steep cracks occur where toppled layers have been rotated to dips of less than 30°. They mainly follow strike joints or combinations of strike joints and bedding surfaces (Fig. 3.17). Where sliding surfaces do not develop, rock masses may be displaced along steep cracks later. Steep cracks are present in both complex multiple block topples and chevron topples.

### 3.6 Topography, toppled volumes and topples

Goodman and Bray (1976) indicated that formation of toppling is controlled by topography, discontinuity orientation and friction angles of penetrative discontinuities on anaclinal slopes. Cruden (1989) gave a criterion for formation of flexure topples on underdip slopes and he also indicated that block toppling on underdip slopes needed some external assistance other than gravity.

After the layers have rotated to dip into slopes, these layers behave like layers on anaclinal slopes. Volumes of toppled rock masses between slope surfaces and surfaces separating toppled and untoppled rock masses vary with different types of topples and discontinuity spacings.

If the simple criterion for toppling given by Goodman and Bray (1976) is not satisfied by the bedding dip and slope angle without considering external forces, toppling should stop. External forces may cause toppled layers to topple further but it is difficult to evaluate external forces quantitatively at this stage. Steeper slopes should cause layers to rotate more.

The studied topples have a large range of current slope angles and toppled bedding dips in the process diagram (Fig. 3.24). Here Friction angles are assumed as 30° which is close to the minimum value of the friction angles of the sandstones in the Spray River Group (Chapter 5). Cohesion is assumed zero because toppled rocks are all close to the ground surface and altered by weathering. All the studied topples except one are far outside the region of toppling from bedding, which indicates these topples except the one in the region of toppling are stable now.

Block flexure topples are characterized by gradual toppling of discontinuities permitting continuous contact throughout the rock mass and transmission of gravitational stresses (Cruden, 1989). As long as the criterion given by Cruden (1989) can be satisfied with respect to topography,

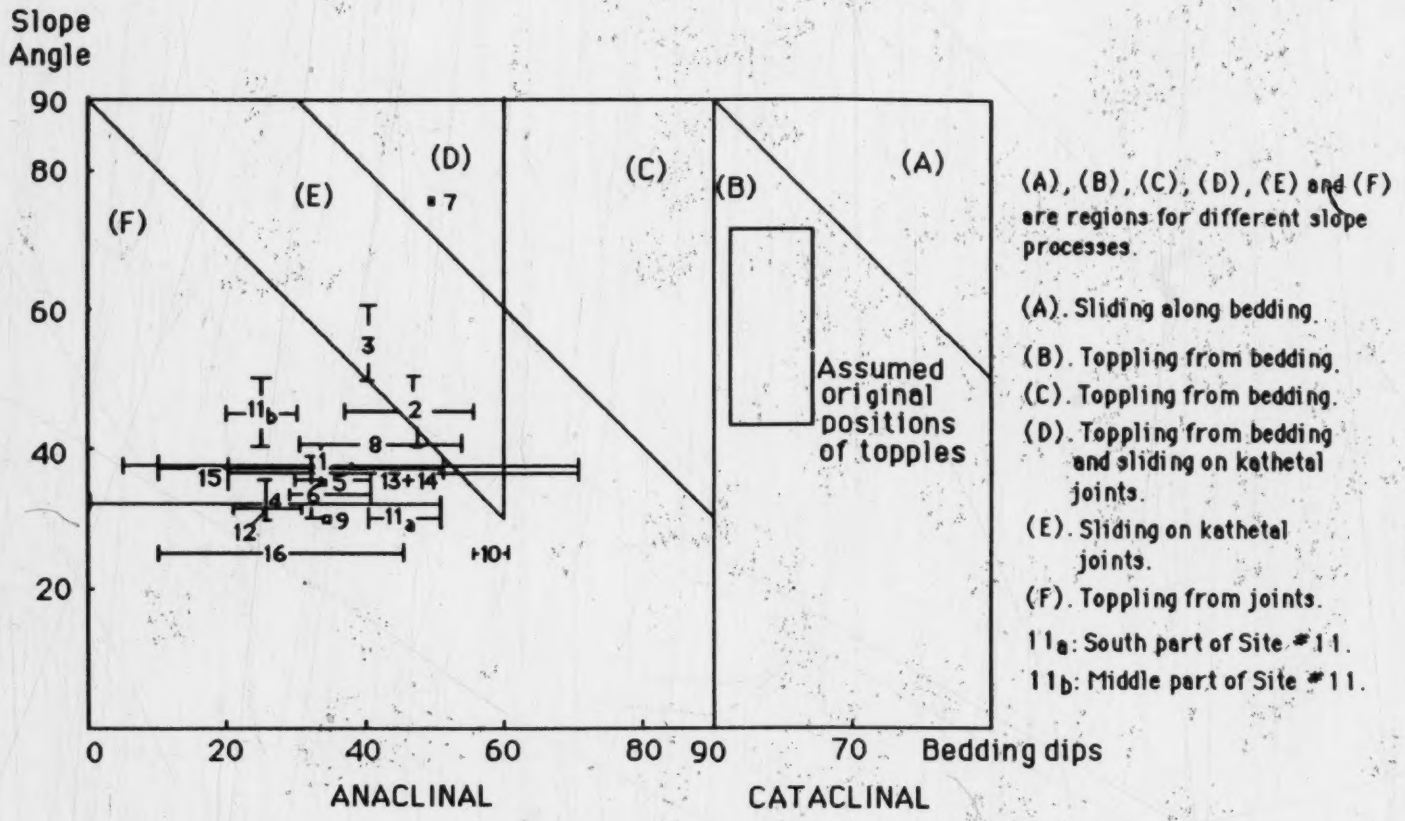
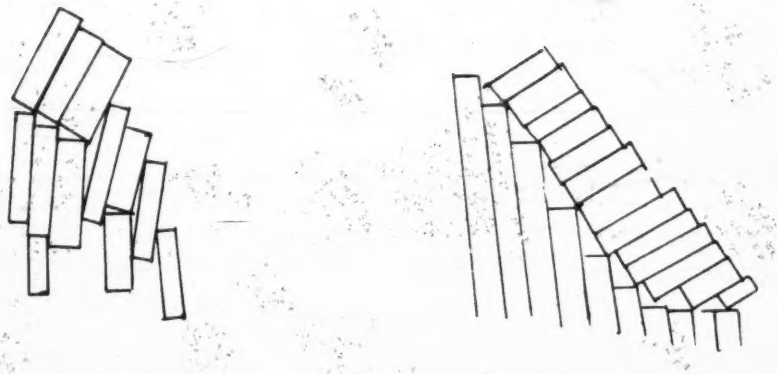



Fig. 3.24. Relationship between bedding dips and slope angles of the topples. The slopes and bedding dips are represented as ranges.

discontinuity orientation and friction angles, toppling can proceed gradually into rock masses producing hinge surfaces, which are close to horizontal in some cases. Volumes of toppled rock masses in block flexure topples in cross section perpendicular to bedding strikes are bounded by slope surfaces, surfaces close to horizontal and surfaces beyond which block flexure topples do not develop (Site 10). Some rock debris may fill in spaces between toppled layers and untoppled layers. Larger block sizes are found to develop larger topples for the studied sites, e.g. the topple at Site 10 is larger than that at Site 4.

Complex multiple block topples develop at different slope angles. But at all the complex multiple-block topples in the Highwood Pass area, overall slope angles are less than 35°. Initiation of toppling at the ground surface may need some external forces similar to those required by block toppling on underdip slopes (Cruden, 1989). Besides pressures from glacial ice, cleft water and freezing processes, deformed weak rocks above the toppled rock masses can also assist. These deformed weak rocks, particularly shales, may push toppled rock masses downslope, e.g. at Sites #9 and #12. Toppled rock masses rotate and cause layers below the toppled masses to topple due to the offset of joint sets along bedding planes (Fig. 3.25), this can be clearly seen from topples in thick layers (Fig. 3.16). Toppling proceeds further down into rock masses as long as rock layers around the surface still topple. Toppled rock



(A) (B)

(A) Block or complex multiple block topples.

Offset of joints against bedding planes causes transgressing of toppling from the ground surface into rock masses.

(B) Chevron topples.

Due to large rotations of rock blocks across the hinge surfaces, offset of joints against bedding planes is broken off. Toppling moments acting on untoppled layers by overlying toppled blocks are much reduced.

Figure 3.25 Effect of offset of joints against bedding planes on toppling

masses are bounded by slope surfaces, hinge surfaces which separate toppled and untoppled layers and some loose materials such as displaced rock masses or deformed shales (Sites 9 and 12). The toppled masses are up to 10 m thick (Site 9).

When slopes are steeper than 35°, chevron topples develop in rock masses with the same structure as those for complex multiple block topples. The only exception is Site #6, where the slope angle is between 30° and 40° and the hinge surface may be formed earlier than the topple formed. Toppled rock masses close to the slope surface rotate large angles to reach stability (Site #3) or sliding surfaces form along hinge surfaces (Site #5). As a result of these uniform large rotations of toppled layers, rock blocks above hinge surfaces separate from the undisturbed rock blocks and the effect of the offset of strike joints is much reduced. (Fig. 3.25). Then forces from toppled masses causing rotation of layers below the hinge surfaces which were transmitted by the offset of the strike joints are also much reduced. Toppled layers can be displaced along hinge surfaces or along steep cracks. Untoppled rock masses are then overlain by toppled layers and it may be more difficult for external effects such as water and ice to reach untoppled layers than before because untoppled layers are covered by toppled layers. Chevron topples are only found close to the ground surfaces. Chevron topples have hinge surfaces more or less parallel to slope surfaces and the toppled rock masses are

less than 3 metres thick perpendicular to slope surfaces at the studied sites.

### 3.7 Toppling processes on underdip slopes

Topples on underdip slopes have many different features which are typical of different topples and different toppling processes.

Block flexure topples may develop under gravity only. Layers dipping steeply SW rotated to dipping NE at 70° to 0°. Bedding layers are gradually folded and no discontinuites formed during toppling. There may not be any rapid mass movements. Rock layers are rotated until block systems are stabilized. Block flexure topples are typical of layers with h/b of 1-2 (Fig. 3.23). Displacement of rock masses along some sliding surfaces in toppled rock masses is possible considering the results of the model tests by Aydan *et al.* (1989) although no such displacement has been found in the studied topples.

External forces may assist initiation of complex multiple block toppling. These external forces may include pressure from water in discontinuities, from freezing processes, from rock debris. Topples of rock layers progress from the surfaces of slopes into rock masses (the regions B and C in Fig. 3.24). Toppled rock masses are bounded by hinge surfaces and slope surfaces. As toppling processes proceed, layers rotate to dip at 40 to 60° into slopes, then sliding surfaces form partly cutting through thin layers and

partly following strike joints (the region E in Fig. 3.24) in thinly bedded units. Sliding surfaces follow the weakest surfaces in thicker units and rock blocks are rotated larger angles by relative dispacement across sliding surfaces than blocks not along sliding surfaces. Preserved sliding surfaces are less than 20 metres long, and rock masses for one single movement are less than 1000 $m^3$ calculated from lengths, widths and thicknesses of the studied topples. Displaced rock masses are not found around the topples and may have been carried away through gullies probably by running water or snow avalanches.

Chevron topples are characterized by steeper slope angles (not less than 35°) than complex multiple block topples. Layers may be rotated large angles because of steep slopes until toppling is stopped. Layers may also be rotated to dip at 40° to 60° into slopes and toppled rock masses move downslope slowly, resulting in small displacements and layers curved across hinge surfaces. Hinge surfaces may also become sliding surfaces, particularly if bedding layers are thin (less than 5 cm). When slope angles are steeper than 40°, toppled rock masses generally rotate to dip 40 to 20° into slopes and steep cracks develop. Slope movements are now slides of rock blocks along steep cracks. Unlike complex multiple block topples, chevron topples involve only rock layers within a few metres from ground surfaces. After toppled rock masses are displaced by sliding along hinge surfaces or along steep cracks, chevron toppling may be

renewed again.

The current slope angles of the topples, except at Site #7, are all less than those required for toppling according to Goodman and Bray (1976) if the friction angle is assumed 30°. It is reasonable to say that all the studied topples are inactive except at Site #7 now. Toppling processes were probably active after the last glaciation because all the topples seem to form after the last glaciation. Slope angles decreased (Fig. 3.24) and led to stable slopes with respect to toppling.

Because most of the toppling sites are far away from toppling regions (Fig. 3.24), external forces must have assisted further development of toppling beyond the toppling-dominated regions.

In the Highwood Pass, the rocks in the Spray River Group change from shales at the top of the toppled ridges to thinly bedded sandstones to laminae of thinly and medium bedded sandstones to thickly bedded sandstones at the toe of the slopes. The change is associated with the change of toppling styles on the slopes. Block flexure toppling dominates around the toes of the slopes if the thickly bedded sandstones are not eroded away. In the middle of the slopes where rocks are thinly to medium bedded sandstones, block topples or chevron topples develop depending on slope angles and bedding thicknesses. Medium bedded layers and steep slopes (more than 35°) favour chevron toppling while thinly bedded layers and gentle slopes (less than 35°)

favour block toppling. In the thinly bedded sandstones at the tops of the slopes, block topples develop with sliding surfaces cutting through thin layers.

### 3.8 Conclusions

Toppling occurs on all the exposures of sandstones, siltstones and shales of the Spray River Group in the Highwood Pass on cataclinal underdip slopes. Toppling processes are controlled by geologic structures and topography and may be assisted by external forces.

Toppling styles are determined mainly by discontinuity spacings. Block flexure topples develop when ratios of joint spacings of strike joints to bedding thicknesses are less than 2. Complex multiple-block topples and chevron topples develop when this ratio is larger than 2.

Block flexure topples develop under the criterion given by Cruden (1989) and toppling retrogresses into rock masses to the surface seperating toppled and untoppled layers. Hinge surfaces develop close to rupture surfaces. There are no sliding surfaces in block flexure topples.

External forces may assist initiation of complex multiple-block topples on slopes gentler than 35° and toppling retrogresses into rock masses to rupture surfaces or hinge surfaces dipping at less than 25°. Sliding surfaces develop in these topples during toppling and they may partly cut thin layers and partly follow joints, dipping at more than 32° or follow combinations of more than one set of

discontinuities, dipping at about 40°. Steep cracks develop when layers have rotated to dip at less than 40° into slopes.

Chevron topples develop on slopes steeper than 35° and toppled rock masses are less than 5 metres thick perpendicular to the slopes. Sliding may occur along hinge surfaces at later stages. Toppled rock masses can fail by sliding along sliding surfaces or by sliding along steep cracks.

The displaced rock masses appear to be stable in the absence of pore pressures or external forces. The topples may be relics of wetter or colder climates.

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# 4. Buckling deformation in the Highwood Pass, Kananaskis Country, Alberta

## 4.1 Introduction

I use the term buckle to describe folds formed close to the ground surface. The amplitudes of these folds are at a maximum at the ground surface and decrease with depth from the ground surface, the axes of the folds lie parallel to the ground surface. Buckles usually occur on steep dip or underdip slopes. Harrison and Falcon (1936) called some naturally formed buckles, roof and wall structures and cascades. Radbruch-Hall (1978) described a few buckles as the results of gravitational creep. Cavers (1981) explained the mechanisms for flexural buckling of plane slopes, three hinge buckling of plane slopes and three hinge buckling of curved slopes. Buckling that Cavers (1981) studied involved one single layer and he also described a buckling case in an open pit coal mine.

Several buckles occur in the quartzites of the Permo-Pennsylvanian Rocky Mountain Group and in the sandstones of the Triassic Spray River Group in the Highwood Pass. Buckles here involve many layers and may not necessarily be at the foot of the rockwall. The buckled layers here can have a larger displacement perpendicular to the layers than those described by Cavers (1981) before the buckled rock masses slide along rupture surfaces. Obviously, the mechanisms of the buckles in the Highwood Pass are more

complex than those described by Cavers (1981).

This chapter first describes four buckles in the Highwood Pass, then analyzes the geological controls of buckling and explains processes of buckling in these examples.

## 4.2 Bedrock Geology

The buckles are located north of Highwood Pass and east of Highway #40 (Figs. 4.1-4.2). The buckles are in the Mississippian Rundle Group, the Permo-Pensylvanian Rocky Mountain Group and the Triassic Spray River Group east of the Lewis Thrust Fault (Bielenstein *et al.*, 1971). The unbuckled bedding planes in the Rocky Mountain Group and the Spray River Group dip at 70°-85°/230°-240°, represented as dip and dip direction. Tear faults perpendicular to the Lewis Thrust Fault also exist offsetting the strata (Allan and Carr, 1947).

The rocks in the Rocky Mountain Group are white to yellow, fine to medium-grained, medium to thickly bedded quartzites. The Spray River Group includes black shales, interlayers of gray, medium to thinly bedded sandstones and sandy limestones and thickly bedded, fine-grained sandstones with shale laminae.

There are five joint sets, strike joints, dip joints, joints subparallel to bedding planes and two other joint sets which are perpendicular to the bedding planes but strike oblique to the bedding planes. Strike joints and dip

Fig. 4.1. Geology around the buckling sites, A.
The figure is based on the airphoto
AS 748 5028 128 (1:15840).
Point "X" is 5.3 km north of the Highwood
Pass parking lot along the Highway #40.
P: Little Highwood Pass parking lot.
B1, B3, B4 are buckling sites.

AS 748 5028 128

Fig. 4.2. Geology around the buckling sites, B.
The figure is based on the airphoto
AS 748 5026 18 (1:15840).
Point "Y" is 1 km north of the Highwood Pass
parking lot along Highway #40.
B2 is the buckling site.

4633-503.6-18
19-7-57

joints are the most common joints in most locations (Fig. 4.3). Unbuckled beds dip at 70° to 85° and due to buckling, buckled beds rotated and have become less steep than unbuckled ones. Dip joints are close to vertical and trend perpendicular to the strike of the beds. Strike joints which were originally close to horizontal have rotated and dip more steeply than strike joints in unbuckled beds. Other joint sets are not clearly shown on Fig. 4.3 due to the small number of measurements.

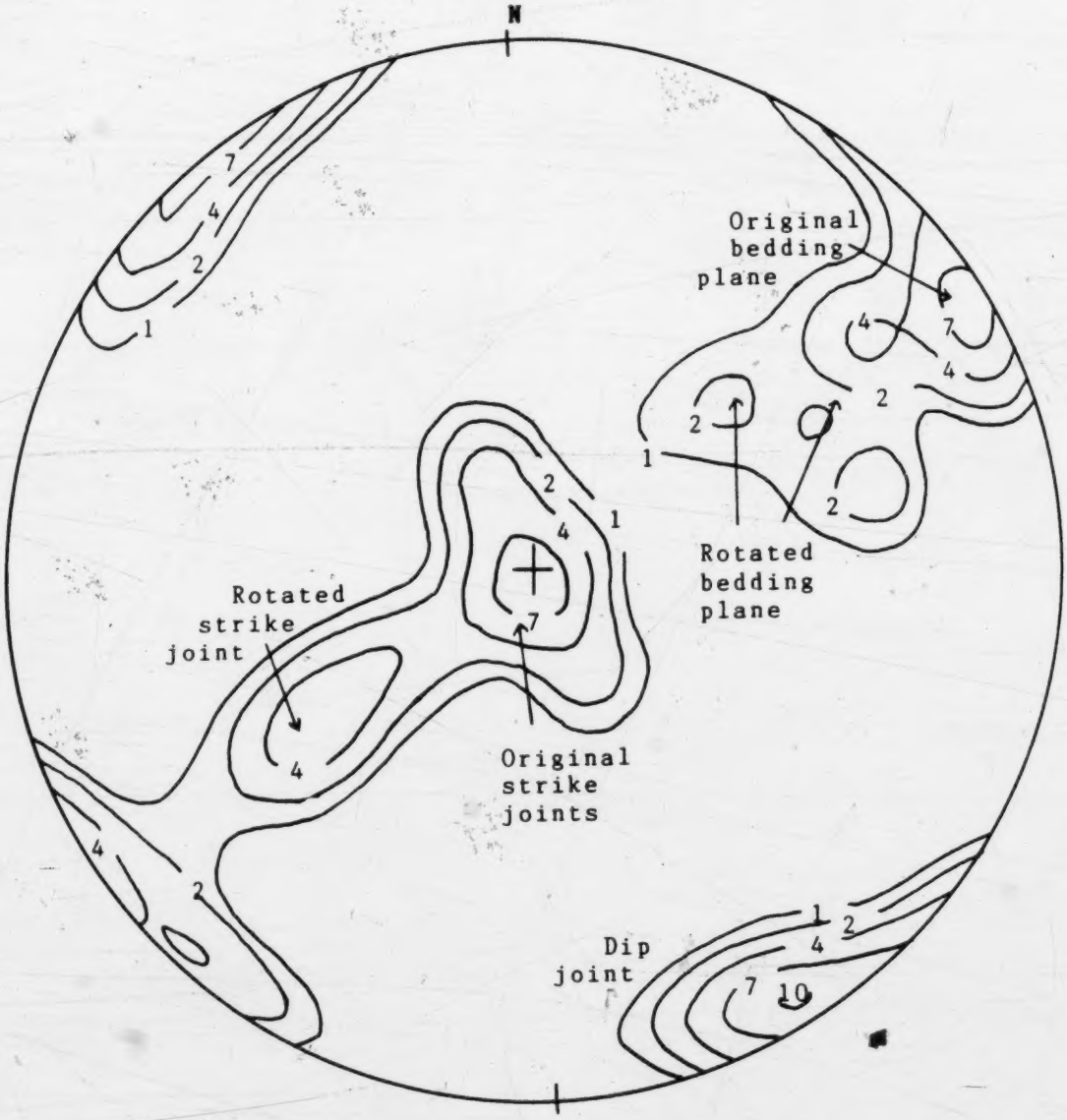
Strength of rock blocks and spacing of discontinuities vary in the rocks, specially in the Spray River Group. Generally, the thicker the beds, the stronger the rock blocks. In the description of the field examples, the uniaxial compressive strength is used, which is estimated by simple field tests (Herget, 1977, p.88).

## 4.3 Field description of the buckling sites

The buckles in the Highwood Pass area were investigated in the summer of 1989. The field investigations conducted include lithology, geological structures and deformations of buckled layers. Four sites were investigated and at each of these sites, buckling deformation has its distinguishing features.

### 4.3.1 Site 1

Site 1 is located 1500 metres east of Highway #40 (Fig. 4.1) and is mainly in the Permo-Pennsylvanian Rocky Mountain




The contour lines are from poles of 105 measurements of discontinuities in the Rocky Mountain Group and the Spray River Formation. Probability diagram (K=100) on an equal angle projection.

Figure 4.3 Structral diagram for buckling sites

Group and a small part of the site is in the Mississippian Rundle Group. Fig. 4.4 shows the south side of the site. The rock slope is a steep dip slope (84°) and the rockwall is over 100 metres high. Layers are buckled either at the foot of the slope or around the middle part of the slope.

The deformation formed as either folding of large wavelength and small amplitude or opening of bedding surfaces followed by relative displacement of rock blocks separated by strike joints to result in convex buckled layers close to the slope surface. The buckles in the middle of Fig. 4.4 show an apparent gradual change of bedding orientations but a close view in the field indicates that the deformation is by opening of the strike joints and the relative rotational displacement of rigid blocks on small scales.

There is an opening of bedding planes around the foot of the wall. The width of the opening is about 1 metre perpendicular to the bedding layers and the opening along the dip direction of the layers is over 20 metres long.

Blocks of three buckled layers are rotated and displaced around the toe of the slope (Fig. 4.5). About ten blocks of less than 1x0.4x3 metres at the bottom moved from the slope surface and an opening was left. The change of dip angles from one block to adjacent block along the same layer is up to 15°. The opening gradually narrowed from the bottom to the top.

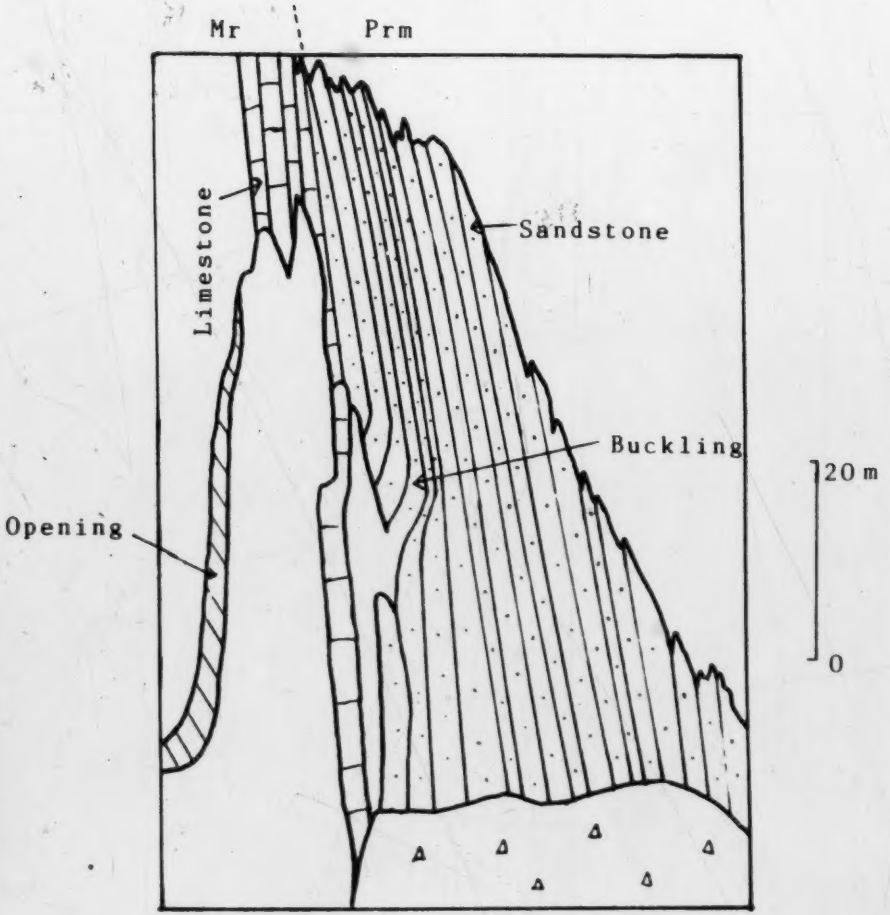



Fig. 4.4. Buckling at Site #1.

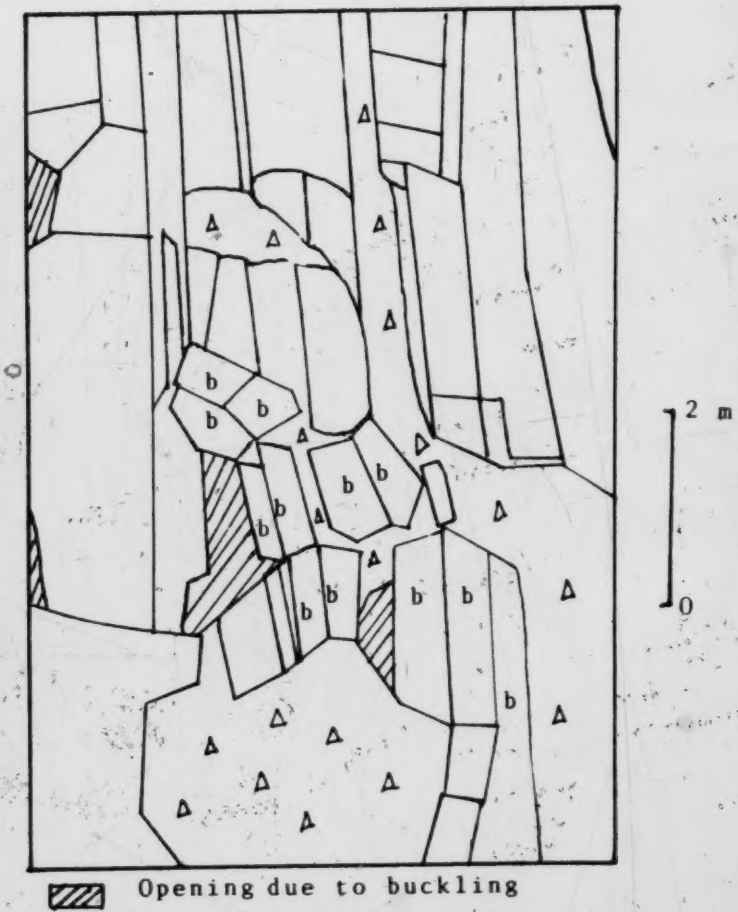



Fig. 4.5. The displaced rock blocks by buckling at Site #1.

The buckle is in quartz sandstones of the Rocky Mountain Group.

Apart from buckles, there are also some small topples on the south side of Site 1 and the thickness of the toppled rockmasses are less than 2 metres.

There are about $2 \times 10^4$ $m^3$ of displaced rock deposited below the rockwall. The distance from the centre of the displaced materials to the rockwall is 200 metres. The debris contains mainly rock masses from the Rocky Mountain Group and a little from the Rundle Group on the upper part. The debris looks fresh. So it is reasonable to assume that the debris and the buckle postdate the last glaciation. There is a rockwall along the boundary of the Rocky Mountain Group quartzites and the Triassic Spray River Group shales. The rockwall was formed by erosion of shales of the Spray River Group along the boundary and the rockwall is the dip slope parallel to the bedding planes of quartzites. The rockwall above the displaced materials was probably higher than other places along the boundary. Buckling may be initiated around the foot or the lower part of the rock wall. Buckles involving one or more than one layer failed along rupture surfaces around the toe of the rockwall. Failed rock masses may slide partly along bedding planes and partly along rupture surfaces. Layer after layer might buckle and fail and the displaced materials were deposited below the rock wall.

The undeformed bedding orientation at Site 1 is 84°/245°. The beds are up to 1.35 m thick with an average about 40-50cm. There are some laminae a few millimetres

thick but these are less than 5% in volume. Joint sets from the thickly bedded layers are 24-30°/155-178° with a spacing of 5 to 10cm, 30°/330° with a spacing of 10 to 25cm and 075°/340° with a spacing of 5 to 15cm.

The uniaxial compressive strengths of the quartzite and the limestones are over 200 MPa by simple field tests (Herget, 1977). Point load tests give uniaxial compressive strengths over 300 MPa.

### 4.3.2 Site 2

This site is located north of the Highwood Pass (Fig. 4.2). The buckle develops on the NW-SE trending ridge is dissected by NE-SW trending gullies. The buckle is in brown, thickly bedded sandstones in the Spray River Group. Buckles are found on the north side of a small gully but not on the opposite side of the gully where a tear fault outcrops. The buckle is estimated to extend less than 150 metres along the strike because the buckle cannot be seen on the other side of the small ridge dissected by the gullies.

The buckled layers at this site are about 50 m long along the dip direction. The dip angles of the buckled layers change from 85° to 60°. In front of the buckles around the foot of the slope, the beds have toppled from dipping SW to dipping NE. The space between the SW dipping beds and the NE dipping beds is filled by rock masses coming from above. Rock layers in front of the buckled layers are broken and loosened but can still be seen in the displaced

rock masses (Fig. 4.6). There is a shallow depression above the gap between the SW dipping layers and the NE dipping layers. No slickensides or other evidence of sliding have been observed in the displaced rock masses.

The buckle is on the steep part of the slope but the rock wall is only about 30 metres high. The whole structure is like the roof and wall structures described by Harrison and Falcon (1936). Buckled layers were smooth without large displacement perpendicular to beds. As buckling of layers proceeded, a knee-fold with a pointed crest formed. Then the knee sheared at the hinge. The lower limb rotated to dip NE forming the toppled part as the upper limb first rested on the lower limb and then slid along the hinge surface of the knee fold. Harrison and Falcon (1936) considered that sliding of the upper limb was along a low-dipping thrust fault. The layers dipping to the NE are at 37-50°/037-054° and the layers dipping to the SW are at 45-85°/257-260°. Strike changes in the toppled layers are probably caused by movements of rock layers towards the gully after the gully was formed. The bedding thickness is about 30-60 cm. The joint spacings are up to 2 metres for those crossing the bedding layers and 5 to 10 centimetres for those extending less than 10 centimetres. The uniaxial compressive strength of the rock blocks is about 200 MPa.

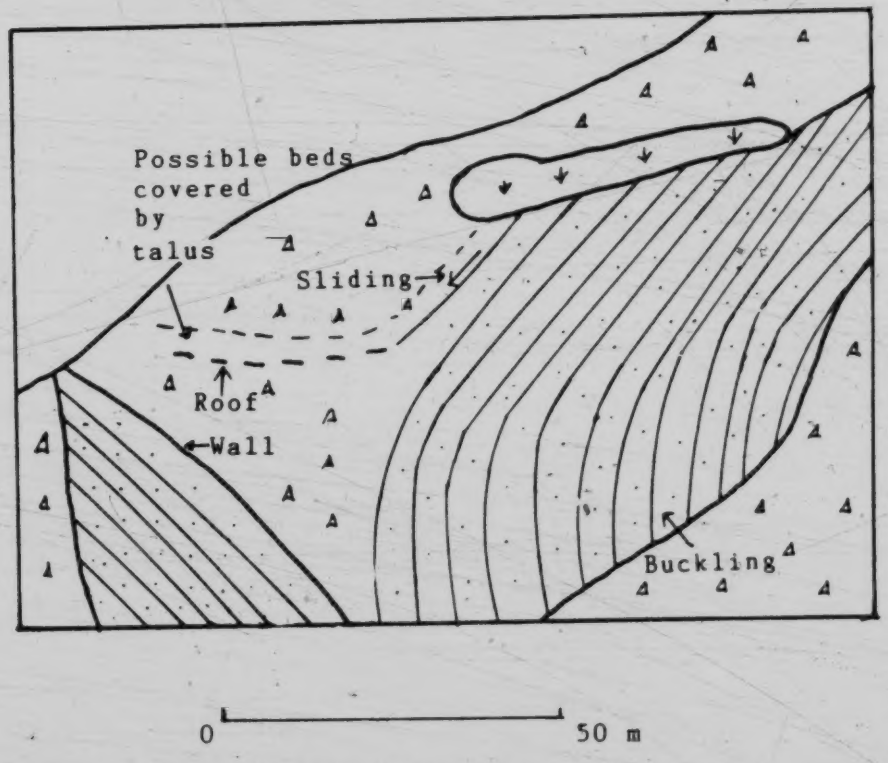



Figure 4.6 Buckling and toppling at Site #2

### 4.3.3 Site 3

The site is located north of the Little Highwood Pass Parking Lot (Fig. 4.1). Buckling is found on the north side of a small gully but not on the other side of the gully and not on the same ridge. The buckle (Fig. 4.7) has an amplitude of up to 3 m wide perpendicular to the bedding planes. The layers change gradually from the buckled zone to the unbuckled zone.

There is a hinge surface which is almost horizontal. The length of the rock layers along the slope surface above the hinge surface is about 10 metres and the local slope angle above the hinge surface is 50-60°. There are also buckles of layers about 2 metres in wavelength. Besides the buckles both at large and small scales, there are some small topples. Both buckling and toppling resemble chevron folds with interlimb angles of less than 150°.

The rocks are thin to medium bedded, light brown to buff-weathering, fine grained sandstones in the Spray River Group. The rock layers below the hinge surface are at 49°/060° and the layers above the hinge surface are at 40-70°/240°. The undeformed layers are at 80°/260°. the strike changes are probably caused by movements of deformed rock layers towards the gully, which suggests that the deformation is not older than the gully. The bedding thickness is 3-10 cm and the joint (dip and strike joints) spacing is from 8 to 20 cm. There are also some thin layers between the relatively thick sandstone layers. The uniaxial

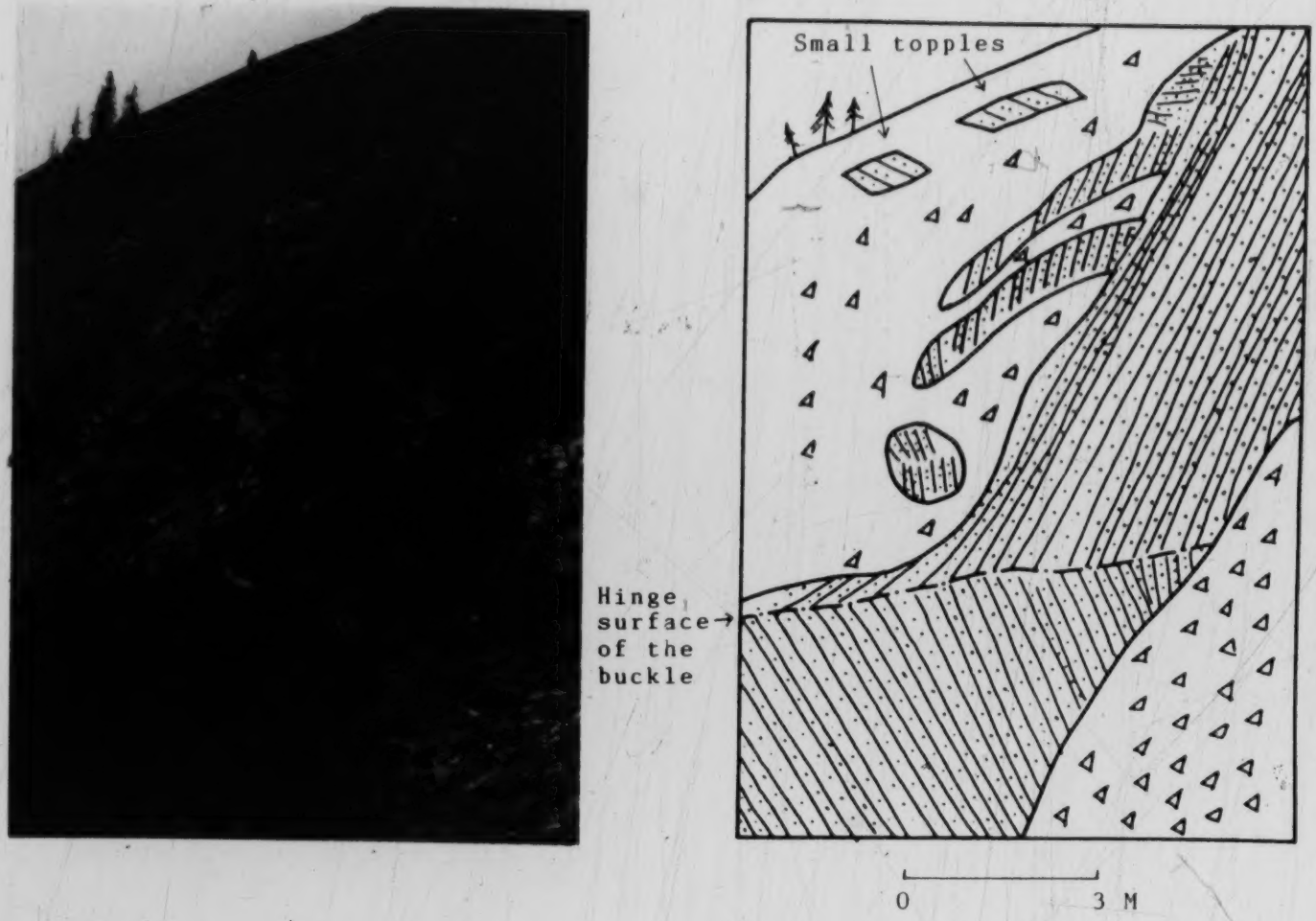



Fig. 4.7. Buckling at Site #3.

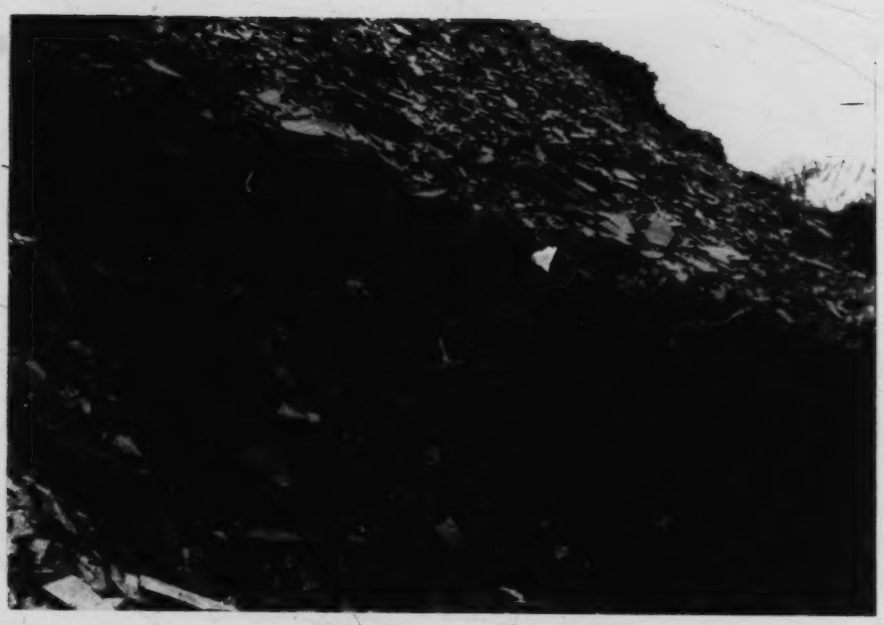
compressive strength of the sandstones is about 200 MPa by the simple field tests.

### 4.3.4 Site 4

The site is on the south side of the creek, south of Site 3 (Fig. 4.1). The buckles are in yellow to brown, thin to medium bedded sandstones of the Spray River Group. Buckling and toppling occur together and the deformed layers are rotated through large angles (Fig. 4.8). The deformed bedding orientations vary from 30°/222° to 38°/055°. The strike rotation occurred for rock layers around the ground surface due to movements of rocks on the slope. The rock masses involving in buckling are less than 2 metres thick perpendicular to slope surface (Fig. 4.9). The buckles are like chevron folds and the lengths of limbs of these chevron folds are less than 20 metres. The hinge surfaces of the buckles are planar and dip NE.

There are many buckles of different sizes and the whole disturbed rock mass is similar to cascades described by Harrison and Falcon (1936). The buckled part of the slope is about 50 m long and the slope angle is 36°. Most of the slope is covered by thin debris. The rock layers 2-3 metres deep into the surface can not be observed at the site but the structure 50 metres north of the site shows the undeformed layers dip steeply SW.

That the buckle is seen only less than 3 metres from the slope surface and the buckle does not extend more than



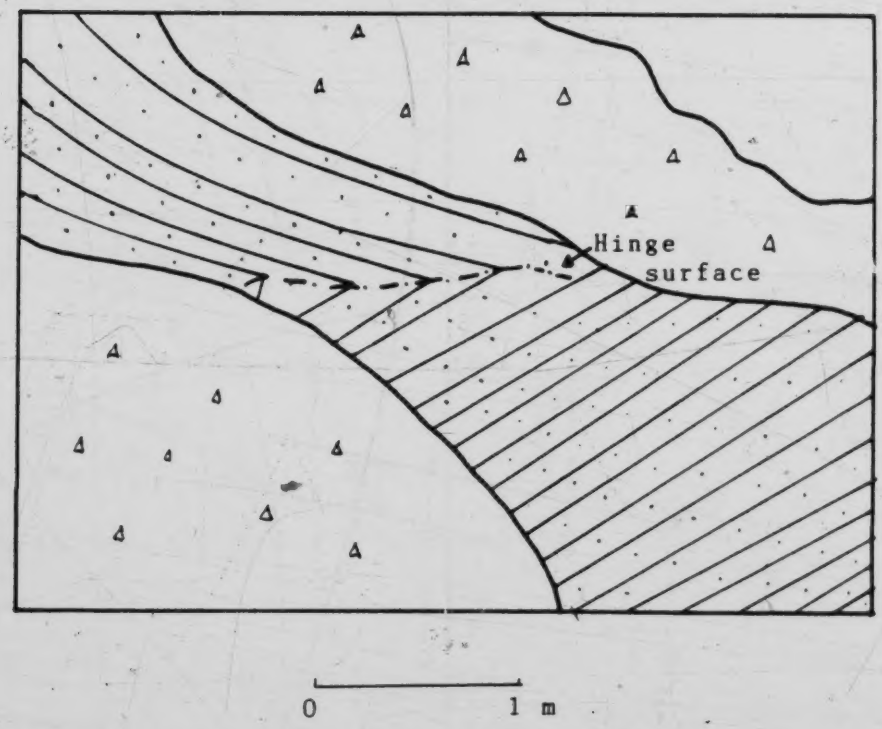



Figure 4.8 Buckling at Site #4

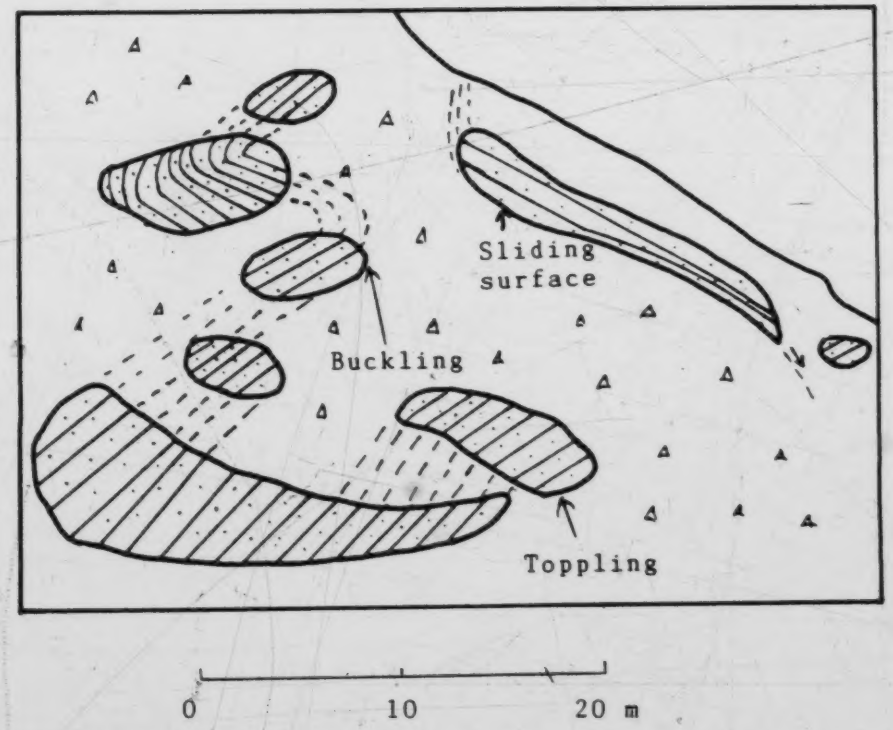



Figure 4.9 Buckles and topples around the ground surface at Site #4

10 metres along the bedding strike suggests that the buckles are only surfacial phenomena and local dilations of the rock masses.

The bedding thickness here is less than 6 cm, mostly less than 3 cm. There are many siltstone or shale layers between the sandstone layers and their thickness is less than 1 cm. The uniaxial compressive strength is from 10 MPa to 200 MPa depending on the bedding thickness. The strength of the layers increases with the bedding thickness.

**4.4 Deformation characteristics and geological controls**

The buckles in the Highwood Pass are not caused by artificial excavations as are those described by Cavers (1981). The buckles studied here formed on natural slopes where the local geology, topography and external forces influence buckling deformation. All the four examples are local loosenings of rock masses due to slope processes rather than folds caused by tectonic movements.

The styles of the buckles in the Highwood Pass are controlled by discontinuity spacings, particularly by bedding thicknesses.

When bedding thicknesses are larger than 30 cm, layers are buckled as,

1. Euler buckles, caused by forces parallel to bedding layers which can be considered as intact materials. Euler buckles have large wavelengths and small amplitudes with wide openings from bedding layers. One

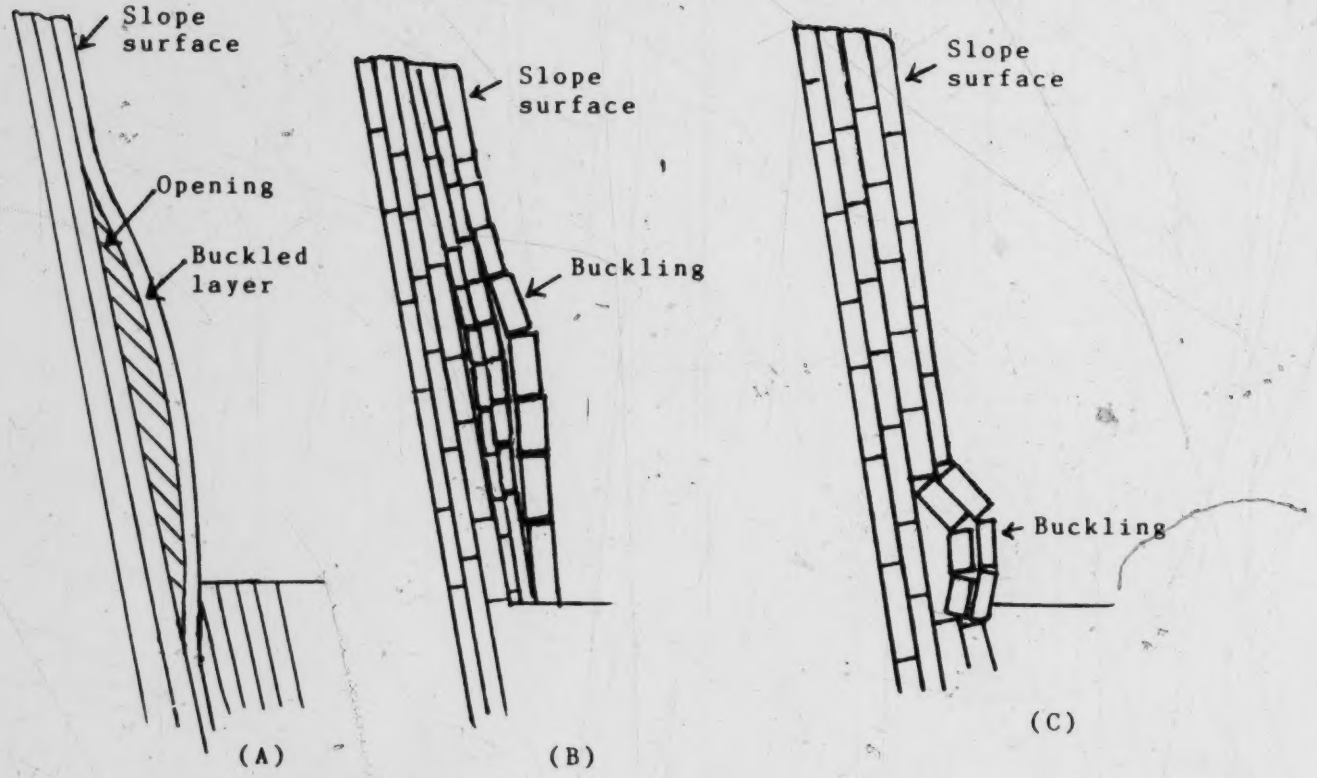



Fig. 4.10. Classification of buckles in thick layers.
(A). Euler buckle.
(B). Block flexure buckle.
(C). Block buckle.

The lines perpendicular to penetrative discontinuities are fractures.

example is the opening formed by Euler buckling on Fig. 4.4. Cross joints are insignificant (Fig. 4.10 A).

2. Block-flexure buckles, in which bedding surfaces of buckled layers form smooth curves on scales larger than individual blocks as the result of relative displacements of blocks along bedding layers. Bedding orientations change gradually from one block to another along bedding layers (Fig. 4.10 B). For example, the buckle in the middle of Fig. 4.4 and the smoothly buckled layers in Fig. 4.6.
3. Block buckles, in which more than two blocks are rotated about hinges which are at intersections of bedding surfaces and joint planes. Rotation angles between adjacent blocks are up to 15°. Openings may be left due to displacements (Fig. 4.10 C). Displacements of blocks are assisted by external forces other than gravity. An example is the buckle on Fig. 4.5.

Wavelengths of buckles in thickly bedded units are related to bedding thicknesses and buckling styles are influenced by external restraints. The ratio of the length of the buckled part to the total length of rock wall of a buckled layer is larger for Euler buckles than those of other types of buckles. Buckled lengths for block buckles are small, only a few blocks around the foot of rockwall are displaced. The observed lengths of driving parts for buckling vary because erosion may occur after buckling and different external forces assisted buckling.

When bedding layers are thinner than 5 cm, buckled layers are like chevron folds. Each layer can be buckled many times. Lengths of limbs are from 2 metres to over 10 metres. Some of buckled layers are rotated to dip at around 30° from original dips of 80°-90°. Preserved hinge surfaces are either close to horizontal or dipping out of slopes. Rock walls are less than 15 metres high at Site #3.

Comparing the buckles with the topples (Chapter 3), I find that chevron buckles, chevron topples and complex multiple-block topples all occur in thin to medium bedded layers. In thick bedded layers in the Spray River Group, both block flexure buckles (Site 2) and block flexure topples (Site 2 in chapter 3) occur.

**4.5 Mechanisms of buckling**

The stability of rockwalls or steep rock layers and the buckling styles of buckles are determined by the responses of rock walls to displacements of the rock layers perpendicular to bedding surfaces. With the same amount of displacement, thick rock walls may still remain mechanically-continuous, steep beams but thin layers with joints may have failed due to rotations of thin tabular blocks about hinge points.

Euler buckling occurs when beds are thick and with few cross fractures. Forces parallel to beds cause large wavelength buckled layers.

When there are cross fractures in thick layers and the displacements perpendicular to the beds are large enough, blocks rotate gradually due to buckling forces and form block flexure buckles. Smaller wavelengths and larger amplitudes than Euler buckles should result for the same bedding thicknesses (the block flexure buckle in the centre and the Euler buckle on the left on Fig. 4.4). More than one layer can be involved in the buckling process (Fig. 4.6).

It is essential to have external forces perpendicular to bedding surfaces for block buckles because of sliding displacements across cross fractures, which left large openings with small wavelengths (less than 5 m) (Fig. 4.5). The effect of external forces on buckling is similar to those for three-hinged buckling of planar beds (Cavers, 1981).

Chevron buckles are formed in thin layers (less than 5 cm ) with a ratio of bedding thickness over joint spacing (h/b) larger than 5. In these layers larger rotations of blocks about adjacent blocks occur than in case of block buckles or block flexure buckles.

**4.6 Buckling processes**

Buckling processes are controlled by the strength of the rocks, the discontinuity spacings of buckled bedding and the stress states during buckling.

Strengths of rock blocks in the Rocky Mountain Group and the Spray River Group are largely dependent on bedding

thicknesses. Strengths of rock blocks in layers more than 30 cm thick are 200 MPa to 300 MPa and those less than 10 cm thick are as low as 80 MPa. Shales in the Spray River Group have uniaxial compressive strengths less than 1 MPa. Buckling of thinly bedded layers requires less driving force than buckling of thickly bedded layers. Buckling needs higher rock walls for thickly bedded layers than for thinly bedded layers if it occurs under self weight. The Euler buckling formula (Cavers, 1981) indicated that the critical buckling load is sensitive to changes of bedding thicknesses because it is proportional to the third power of the bedding thickness.

Stress states are determined by topography and external forces. Possible external forces include pressures from water in the discontinuities and from the freezing of this water.

Discontinuity spacings of blocks define sizes and shapes of blocks, the most important factors in the response of layers to buckling.

Thick beds are characterised by Euler buckles, block-flexure buckles and block buckles. When there is a rock wall, Euler buckles can form at the toes of rock walls being driven only by rock weight. Magnitudes of openings formed as the result of buckling are related to bedding thicknesses and other mechanical properties of rocks according to the Euler buckling formula. Block-flexure buckles form where beds have closely spaced strike joints.

While bending of beds occurs in a Euler buckle, only rotations of rigid blocks occur in a block flexure buckle. Dip angles of blocks along a bed change gradually from one block to adjacent ones. Block buckles are assisted by external forces perpendicular to bedding surfaces.

Thin layers buckle like kink folds. It is much easier for blocks to be rotated by external forces because ratios of joint spacings to bedding thicknesses are larger and sizes of blocks are smaller than in thickly bedded layers and it is easier for the ends of blocks to yield under compression stresses than thick layers. High rock walls are not necessary for buckling. Buckles always involve more than one layer.

After buckles are formed and grow, the structures of rock blocks become unstable, buckled layers are rotated and displaced by downslope movements of rock masses around slope surfaces. The hinge surfaces of the buckles become inclined, dipping into slopes and interlimb angles are decreased. The interlimb angles are as low as 50° (Site 4). The series of chevron folds at Site 4 are cascades and roof and wall structures have formed at Site #2. If buckles are unstable, rock masses can also be displaced and deposited below the buckled beds (Site 1).

The buckles that Harrison and Falcon (1936) described were up to about 1500 metres in length, which is a lot larger than those in Kananaskis Country. The buckles in Kananaskis Country are less than 200 metres in length.

Perhaps strong physical weathering above the treeline in the Canadian Rockies induced buckles at shallower depth than those described by Harrison and Falcon (1936). The buckles of Harrison and Falcon (1936) were in south-western Iran and the climate there is drier than in the Canadian Rockies and without freezing and the other influences in cold and wet climate.

## 4.7 Conclusion

Buckles take place on steep dip slopes and buckling styles of bedding layers are controlled by geological structures, particularly discontinuity spacings. Lengths of dip slopes can be as low as 10 metres in thin beds on natural slopes.

Buckles of layers thicker than 30 cm can be divided into Euler buckles which have no cross fractures, block-flexure buckles which have shapes similar to Euler buckles but with cross fractures and block buckles with displacements across cross fractures.

Euler buckles and block buckles develop only at the ground surface but block flexure buckles can develop into rock masses and involve more than one layer of rock.

When bedding thicknesses are less than 5 cm, chevron buckles develop. Bedding dips change abruptly across hinge surfaces.

Buckles can develop into roof and wall structures or cascades or fail. Rock volumes up to $2 \times 10^6 m^3$ of buckled rock

masses can be displaced.

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# 5. Portable tilting table

## 5.1 Introduction

Sliding of rock masses along penetrative discontinuities can be simulated by rock blocks sliding along inclined planes. Shearing strengths along penetrative discontinuities are determined by friction and cohesion along the sliding planes.

Determination of friction angles of rocks and discontinuities is essential for evaluation of stability of rock slopes. The use of direct shear boxes requires careful transport of specimens from the field, cutting rocks to specified shapes, lapping rock surfaces if necessary and spending at least a day to test a sample. Since Hoek and Bray (1974) first suggested that the angle of friction could be obtained by a simple tilt test when a clearly defined failure surface existed, friction angles of artifitial rock surfaces and natural discontinuities have been tested by tilting by Cawsey and Farrar (1976), Barton and Choubey (1977), Bruce *et al.* (1988) and Cruden and Hu (1988). Hencher (1976) discussed advantages and limitations of tilting tables.

Testing rocks in the laboratory using a tilting table requires transportation of rock samples from the field and, generally, cutting of rock samples in the laboratory. Only a limited number of rock samples can be tested if the working site is far from a highway. Rock samples may be broken when

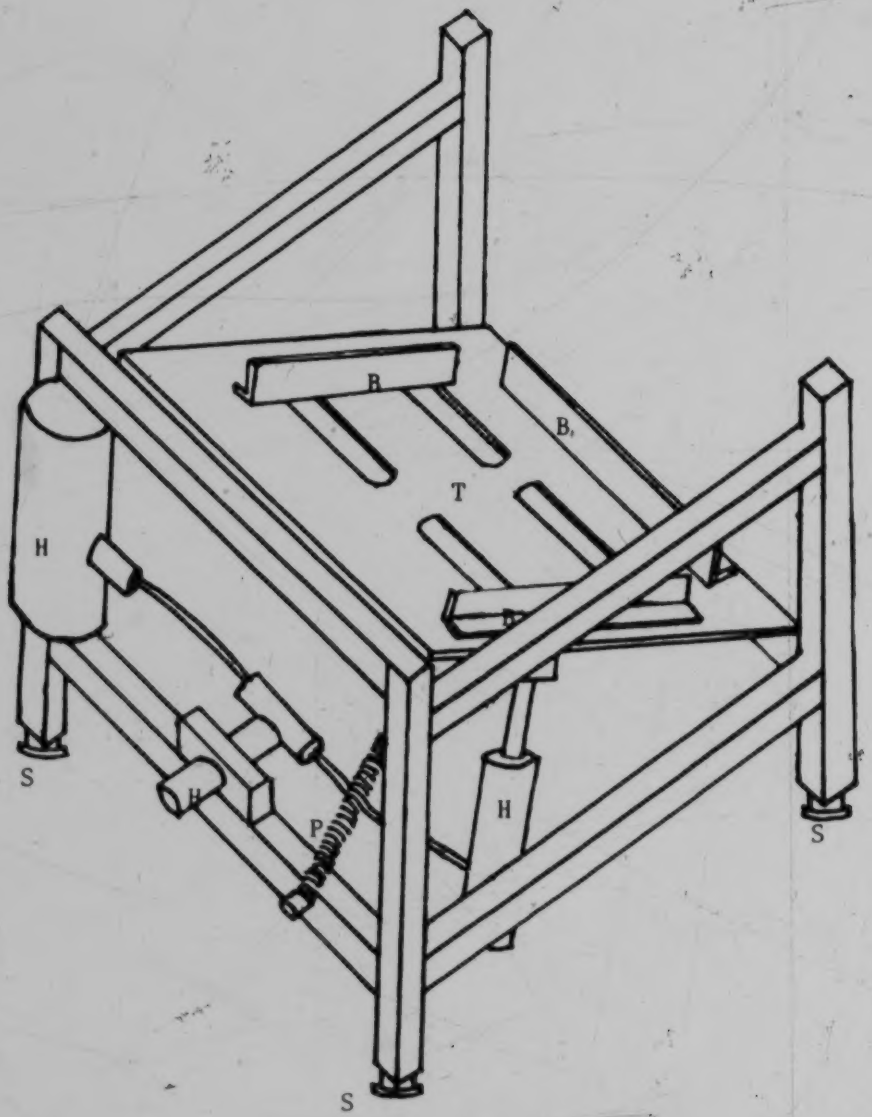
they are sawn. In order to conduct as many tests as needed in the field, a portable tilting table was designed by the author and built in the Department of Civil Engineering workshop at the University of Alberta. The tilting table was used to test friction angles of bedding surfaces of sandstones in the Highwood Pass, Alberta. A report on the tilting table is given here.

The construction of the tilting table and the test procedure are described first, followed by testing examples of the rocks at the Highwood Pass. Then, a discussion of the testing results and the table itself is given.

## 5.2 Construction of the tilting table

The tilting table was constructed to have rock samples on the table gradully tilted until sliding being reached between rock samples. A hinged table is supported by a rigid frame (Fig. 5.1). A spring and hydraulic pressure system is used to rotate the table. The spring pulls and tilts the table and the hydraulic system controls the flowing rate in the system by a switch, which determines the rotation rate of the tilting table. The table rotates from 0° to 46°.

The tilting table is made from aluminum plate for lightness and can be carried in the field for long distances. The weight of the table is 2.2 kg. The dimensions of the frame are 22.5 cm x 22.5 cm x 18 cm. A screw under each foot of the frame can level the frame for testing. The hinged table is equipped with brackets to hold samples up to




T: Tilting table
B: Brakets
H: Hydraulic system
S: Ajustable screws
P: Spring.

Fig. 5.1. The portable tilting table.

16 cm x 16 cm. The parts of the table are bolted together when transported. Samples from 12 cm to 30 cm thick can be tested.

**5.3 Test procedure**

First the tilting table is set up in the field. The four foot screws are adjusted to level the table using a fish-eye level.

After samples are collected, the bottom sample or plate is placed on the table and held by the brackets. A fish-eye level is placed on the sliding surface and the screws are adjusted to level the sliding surface at the beginning of the test. This leveling is repeated for each new sample to make the sliding surface horizontal at the beginning of the test. Then the upper sample or slider is placed on the bottom one or plate. The switch of the hydraulic system is turned open to let the tilting table rotate at 10°/minute. I found that sliding angles did not change noticeably for the rotation rate in the range of 5° to 10°/minute. In order to compare testing results of the portable tilting table with those from a lab tilting table with the rotation rate of 8°/minute, 10°/minute was chosen for the field tests. The angle at which the slider has slid 2 mm is recorded as the sliding angle because the slider generally accelerated after sliding 2 mm. Sliding angles are calculated by the measurements of the vertical displacements of the displaced end of the table and the length of the table.

Repeated tests were performed with both the plate and the slider oriented in the same way. Each sample is tested four times and the average is taken as the friction angle. Sliding angles did not vary in systematic ways for the four tests conducted on samples.

**5.4 Testing of bedding surfaces at Highwood Pass**

The testing was conducted around Highwood Pass and the samples were taken from the Triassic Spray River Formation (Allan and Carr, 1947) which was later raised to Spray River Group (Irish, 1965). The rocks tested are thinly to thickly bedded, brown to yellowish, fine grained sandstones with some shale and silt laminae. Thicker sandstone layers are stronger than thinner layers. Strengths of testing samples were rated as R1 to R5 and S5 to S2 (Herget, 1977, P.88).

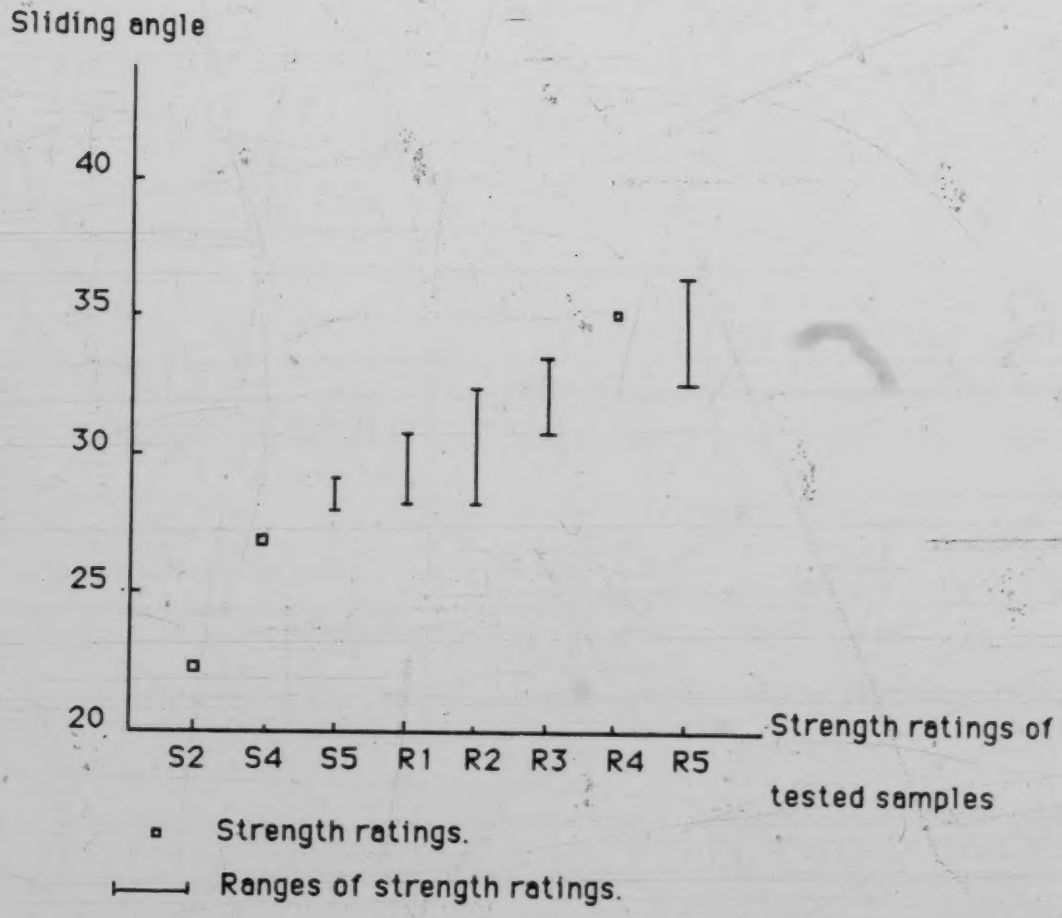
Samples were selected to have as smooth testing surfaces as possible. Dimensions of the samples were measured and strengths of the blocks were estimated and rated using the geological hammer (Herget, 1977).

34 samples were tested using the tilting table (Table 5.1). Sandstone samples have friction angles of 28° to 36° and the sandstone and shale laminae, the siltstones and the shales have friction angles between 22° and 30°. The samples were taken at the ground surface and in dry weather. There is an overall trend that the sliding angles increase with the strengths of blocks (Fig. 5.2).

Table 5.1 The testing results from the portable tilting table

| Sample | Lithology | Discon. | Thi.(cm) | Dimension (cm) | Mean (degree) | S.D. | Rating |
|---|---|---|---|---|---|---|---|
| 1 | ss | b | 2 | 17x17x4 | 33.1 | .63 | R3 |
| 2 | ss | b | 3 | 16x10x8 | 32.5 | .35 | R3 |
| 3 | ss | b | 3 | 14x14x8 | 32.7 | 1.11 | R3 |
| 4 | ss | b | 2 | 18x16x7 | 30.7 | 1.18 | R3 |
| 5 | ss | b | 3 | 18x15x7 | 32.5 | 2.00 | R3 |
| 6 | ss | b | 2 | 17x16x4 | 33.3 | .74 | R3 |
| 7 | ss | b | 2 | 15x10x5 | 32.1 | .56 | R3 |
| 8 | ss | b | 2 | 20x16x5 | 32.5 | 1.23 | R3 |
| 9 | ss | b | 1 | 16x16x6 | 31.1 | .52 | R2 |
| 10 | ss | b | 1 | 16x12x2 | 30.3 | .93 | R1 |
| 11 | ss | b | 2 | 15x10x8 | 30.0 | .96 | R1 |
| 12 | ss | b | 2 | 18x14x6 | 30.4 | 1.29 | R1 |
| 13 | ss | b | 3 | 19x9x9 | 30.4 | 1.29 | R1 |
| 14 | ss | b | 1 | 9x8x6 | 28.3 | 1.99 | R2 |
| 15 | ss | b | 3 | 18x12x12 | 32.5 | .38 | R5 |
| 16 | ss | b | .5 | 18x13x4 | 32.2 | .46 | R2 |
| 17 | ss | b | 3 | 18x12x12 | 32.3 | .33 | R2 |
| 18 | ss | b | 3 | 18x13x10 | 35.1 | 1.46 | R4 |
| 19 | ss | j | 3 | 18x16x10 | 34.9 | 1.38 | R5 |
| 20 | ss | b | 3 | 16x16x13 | 33.5 | .64 | R5 |
| 21 | ss | b | 2 | 17x15x6 | 30.7 | .61 | R1 |
| 22 | ss | b | 2 | 13x12x6 | 36.3 | .59 | R5 |
| 23 | ss | b | 2 | 16x8x7 | 32.1 | .38 | R3 |
| 24 | ss | b | 3 | 16x13x12 | 35.8 | 1.05 | R5 |
| 25 | ss with sh | b | 1 | 18x10x8 | 29.7 | 5.37 | R1 |
| 26 | ss with sh | b | .5 | 12x12x4 | 29.1 | .94 | S5 |
| 27 | ss with sh | b | 1 | 16x13x7 | 26.8 | .20 | S4 |
| 28 | ss with sh | b | 1 | 15x10x7 | 28.8 | 3.18 | R1 |
| 29 | ss with sh | b | .5 | 17x16x3 | 30.7 | 1.11 | R1 |
| 30 | ss with sh | b | .5 | 18x16x3 | 28.3 | 1.82 | R1 |
| 31 | ss with sh | b | .5 | 17x15x5 | 29.6 | .79 | R1 |
| 32 | ss with sl | b | 2 | 12x10x6 | 28.7 | 2.37 | S5 |
| 33 | sh | b | .2 | 17x14x4 | 28.2 | 3.26 | S5 |
| 34 | sl | b | .2 | 10x10x3 | 22.4 | 1.65 | S2 |

Discon.: Types of discontinuities.
Thi.: Minimum thickness of layers or blocks tested.
Mean: Mean sliding angle.
S.D.: Standard deviation of sliding angles.
Rating: Strength rating of rock blocks ( Herget, 1977).
ss: Sandstones.
sh: Shales.
sl: siltstones.
b: Bedding surfaces.
j: joint surfaces.




S2, S4, S5, R1, R2, R3, R4 and R5 are strength ratings of rock blocks, based on the system of Herget (1977)

Figure 5.2 Relationship between strengths of blocks and sliding angles

A few sandstone samples from the Spray River Group in the Highwood Pass were tested on a tilting table in the laboratory (Table 5.2). Their strengths are rated as R3 to R4 (Herget, 1977). All the samples were tested four times at the rotation rate of 8°/minute. Two samples were sawn to 5 cm x 5 cm and up to 2 cm thick and the plate were lapped with #80 grit and tested. Then the sliders were lapped and then tested. Sliding angles from surfaces lapped with #80 grit can be used as an estimate of basic friction angles of the rock. 5 samples of natural surfaces were also tested.

The lapped surfaces have sliding angles 28° to 29°. Natural surfaces over lapped surfaces give sliding angles of 30° to 33°. For each sample, the mean sliding angle from two lapped surfaces and that from a natural slider are significantly different at the level of 95% by t-test. Natural surfaces over natural surfaces give sliding angles of 32° to 52° depending on surface roughness. The mean sliding angles from 5 samples are significantly different at the level of 95% by F-test. The large range of sliding angles from natural surfaces resulted from different roughnesses.

## 5.5 Discussion of testing results

The sliding angles of most sandstone samples from the portable tilting table are higher than that from two lapped surfaces in the laboratory test, which indicates that discontinuity surfaces in the field are rougher than

Table 5.2 Testing results from the lab tests

| | Natural surfaces over natural surfaces | | | | |
|---|---|---|---|---|---|
| Samples | 1 | 2 | 3 | 4 | 5 |
| Sliding angles | 52±3.1 | 37±0.1 | 53±2.5 | 36±2.5 | 32±1.5 |

| Samples | Lapped surfaces over lapped surfaces | Natural surfaces over lapped surfaces |
|---|---|---|
| 1 | 29±3.2 | 33±1.3 |
| 2 | 28±1.0 | 30±1.0 |

The sliding angles are presented as the mean sliding angles and the standard deviations.

surfaces lapped by #80 grit. In the laboratory testing, the rougher natural surfaces over lapped surfaces gives higher sliding angles than two lapped surfaces. Natural surfaces can give considerably high sliding angles if surfaces are very rough. So the roughness of discontinuity surfaces control sliding angles of samples if the lithologies are the same.

In the field, stronger sandstone samples gave higher sliding angles. This may be caused by asperities on sliding surfaces of weaker sandstones chipping off more easily in sliding than those of stronger sandstones. Weaker sandstones are not as well cemented as stronger ones.

Bedding surfaces of shales and siltstones have lower sliding angles than those of sandstones. Some fine particles produced during sliding may smooth sliding surfaces of shales and siltstones because shales and siltstones are weaker and not well cemented compared to sandstones. Sandstones are harder than shales so it is difficult to produce fine materials from sliding under low normal loads. Where rocks are laminae of sandstones and shales and siltstones, friction resistance is controlled by shales and siltstones.

The portable tilting table is only suitable for smooth discontinuities, such as bedding surfaces and probably smooth sliding surfaces. Rough surfaces of discontinuities such as rough joint surfaces are not suitable for testing using the tilting table because the tests on rough surfaces

involve toppling of testing blocks sometimes, which generally results in large angles. It is generally possible to find smooth surfaces of discontinuities from bedding planes. So it is practical to get good estimates of friction angles of bedding planes from as many tests as desired.

The lowest average sliding angles from 4 samples of sandstone surfaces using the portable tilting table are close to those tested in the laboratory for sandstone samples lapped with #80 grit, so results from the portable table can be used as estimates of the basic friction angles of rocks if the sample discontinuities are smooth enough.

The results from the field tests show that the minimum sliding angle on sandstone samples is close to the basic friction angles obtained from the laboratory tests. Siltstones and shales have lower sliding angles than sandstones. Siltstones and shales can be located and tested satisfactorily in the field but may not survive transportation and cutting on the rock saw.

## 5.6 Conclusions

The portable tilting table is useful equipment for tilting tests in the field. As many smooth discontinuity surfaces as desired can be selected and tested. The minimum sliding angle from smooth surfaces can be used as an estimate of the basic friction angle of discontinuities in sandstones. Siltstones and shales can also be tested in the field when they may not survive transportation.

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# 6. Processes, slope movements and landforms in stratified rocks

## 6.1 Introduction

Heights and gradients of rock slopes are controlled by orientations and locations of discontinuities and orientations of slopes as well as strengths of rock masses. In stratified rocks, slope movements of rock masses are mainly controlled by penetrative discontinuities parallel to each other and joints which are generally perpendicular to penetrative discontinuities. Landforms are modified by slope movements which are related to orientations of discontinuities. Sliding along penetrative discontinuities forms dip slopes parallel to sliding planes but landforms produced by other slope movements are not that simple. The mode of movements of rock masses in stratified rocks can be sliding either along penetrative discontinuities or across them, falling, buckling or toppling in stratified rocks. Displacements of rock masses are either through catastrophic movements or through noncatastrophic movements of rock blocks such as toppling of individual blocks followed by sliding.

Terzaghi (1962) gave a model to determine slope angles of slopes in stratified rocks when layers dip into slopes with some cross joints assumed to be arranged regularly in different ways but no field cases were reported. Toppling was not recognized in Terzaghi's model. Selby (1980)

concluded that slope profiles are functions of rock block strengths, discontinuity spacing, infill materials within discontinuities, ground water and weathering conditions if slope developments are not controlled by structures or oversteepened. But processes and mechanisms by which slope movements modify landforms in stratified rocks have not been studied systematically.

Sauchyn (1984) mapped 56 open rock basins in Kananaskis Country using airphotos and concluded that the geometries of the open rock basins are determined by three principal factors, size, shape and gradient by a factor analysis (p.137). Open rock basins are rock chutes, funnels or open cirques dissecting rockwalls (Sauchyn, *et al.*, 1990). Rock masses are moved in open rock basins and formation and development of rock basins modify landforms created by the glaciations. To study the relationship between slope movements and landforms in stratified rocks using the geometrical data of Sauchyn (1984), I investigated the geological structures and bedrock slope angles of 55 of these basins in the summer of 1988 and 1989 (Fig. 6.1). Sauchyn *et al.* (1990) concluded that shapes and sizes of rock basins are mainly controlled by slope types based on the relationship between orientations of penetrative discontinuities and of slopes (Cruden and Hu, 1990). But the relationship between slope gradient and slope movements controlled by structures for these rock basins has not been evaluated.

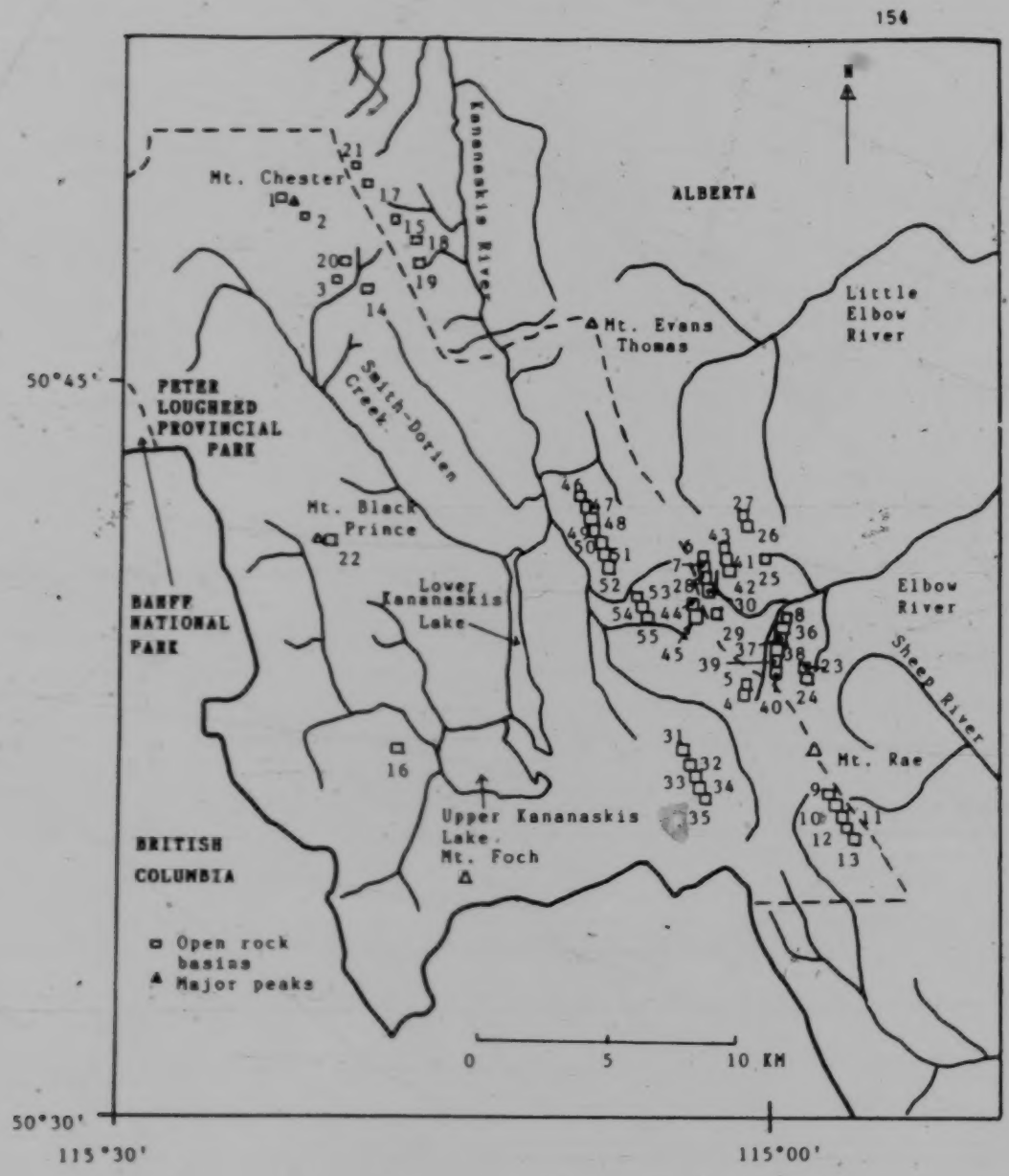



Figure 6.1 Locations of the open rock basins

This chapter examines the relationship between slope gradient and slope movements in stratified rocks based on my studies of slope movements on all types of slopes in Kananaskis Country in the previous chapters and the data from the open rock basins of Sauchyn (1984). Slope movements on different types of slopes are briefly reviewed first and followed by detailed descriptions of slope movements on orthoclinal and plagioclinal slopes because there are no such descriptions in the literature. Finally the relationship between processes of slope movement and landforms is discussed.

## 6.2 Slope movements on different types of slopes

### 6.2.1 Cataclinal overdip slopes and dip slopes

Sliding along penetrative discontinities is the main slope movement on cataclinal overdip slopes. There is no lateral restriction for slope movements if rock slopes are cut by two gullies in the direction of sliding.

Friction and cohesion along bedding planes provide sliding resistance. Basic friction angles can be used as estimates of friction angles along bedding surfaces in the Rockies if the bedding surfaces are not altered or softened (Cruden, 1985). Sliding only occurs when bedding dips exceed basic friction angles of rocks and both friction and cohesion are overcome (Hoek and Bray, 1977). Sliding of rock masses produces dip slopes parallel to sliding planes. If

the bedding dip on a slope exceeds the basic friction angle but the sliding force can not overcome cohesion along the potential sliding plane, the slope remains as an overdip slope.

Cruden (1975) showed a slab of thickness, $H\cos\psi$, can be supported by a cohesion, c, where

$$H\cos\psi = c\cos\phi/\gamma g\sin(\psi-\phi) \qquad (1)$$

Where H is the thickness of the slab measured in the vertical direction, c is cohesion, $\psi$ is the bedding dip and $\phi$ is the friction angle.

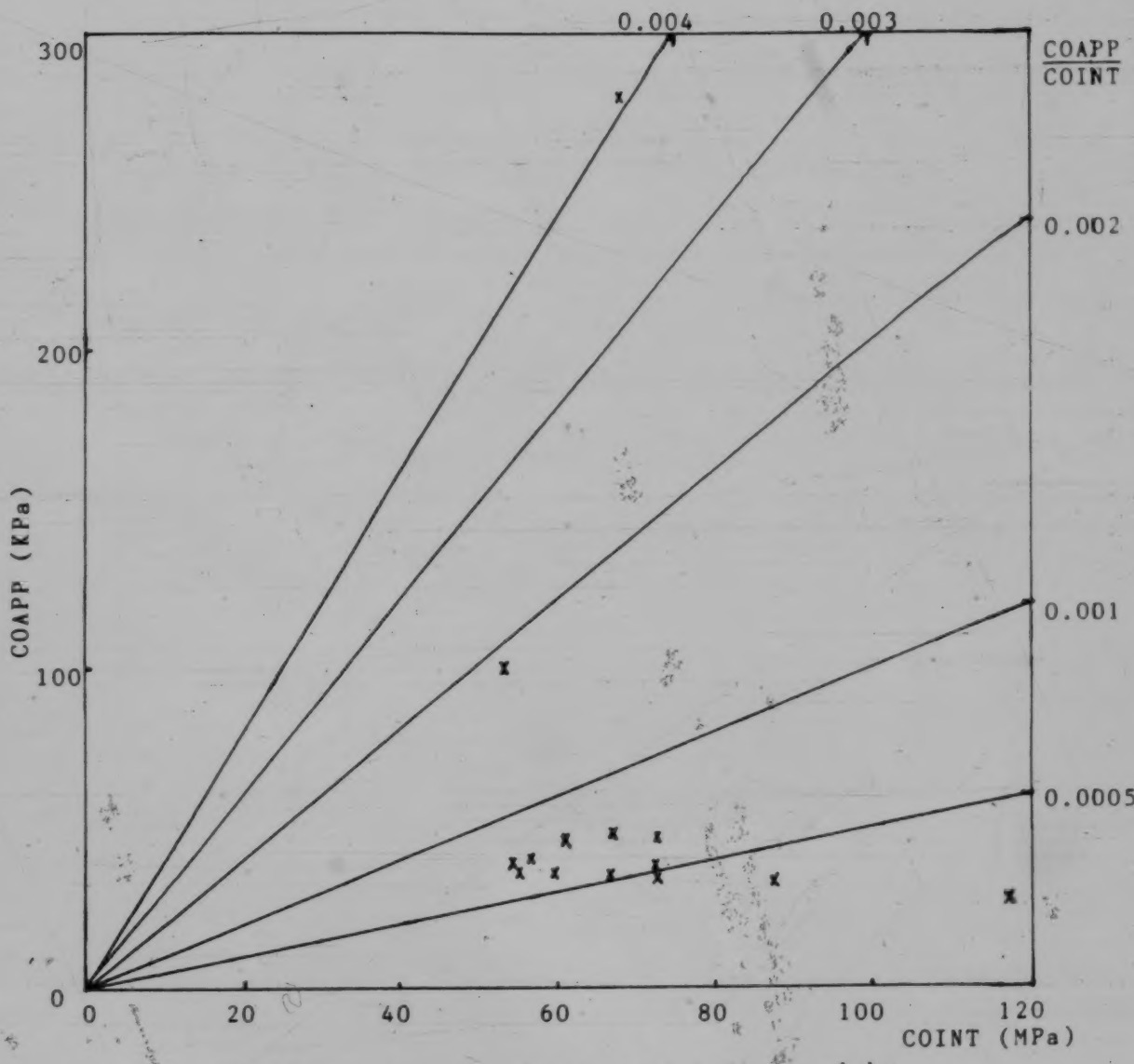
Eaton (1986) identified 80 slope movements on dip and overdip slopes and mapped 53 stable overdip slopes on the airphotos. I investigated 43 of them, the others are either small or inaccessible. 14 overdip slopes have bedding surfaces as potential sliding surfaces that are steeper than the basic friction angles of rocks (Hu, 1987). I calculated lower bounds of apparent cohesion using equation 1 for these 14 overdip slopes in Kananaskis Country where the dip angles of the bedding surfaces exceed the basic friction angles (Hu, 1987). The basic friction angles were estimated by tilting tests on sawn and lapped surfaces (Cruden and Hu, 1988, Hu, 1987). Roughness angles were taken as zero at the scales of blocks capable of sliding based on the field observations.

The calculated lower bounds of cohesion include both the rock-bridges and the apparent cohesion from smaller scale roughness than potential sliding blocks. The lower

bound of cohesion is between 28 KPa and 47 KPa, equivalent to less than 0.1% of cohesion for intact rocks for 12 slopes (Fig. 6.2). The cohesion for intact rocks were calculated from the uniaxial compressive strengths and friction angles derived from Mohr-Coulomb criterion (Goodman, 1980, p. 77). The uniaxial compressive strengths were determined by the indentation tests (Hu, 1987, p. 212) and the basic friction angles were used as estimates of the friction angles.

The lower bound of cohesion for one of the remaining two slopes from the 14 slopes is 100 KPa. The basic friction angle on this slope is low and may underestimate friction over the whole potential rupture surface because the basic friction angle along bedding changes rapidly due to different grain sizes of carbonates (Hu, 1987). The other high cohesion estimate, 280 KPa, may be due to a curved potential rupture surface and an oversimplification of the back calculation.

It is difficult to measure the rock bridges which provide cohesion in the field. Rupture surfaces are largely inside rock masses and rock bridges measured from traces of bedding surfaces on surfaces cutting beds may not represent the real rock bridges of the potential sliding surfaces. For instance, the proportion of rock bridges estimated from traces may not be the same as the proportion of rock bridges on the whole rupture surface if rock bridges along a bedding surface are not randomly arranged. Furthermore, I have not seen rock bridges along penetrative discontinuities in the




COAPP: lower bounds of cohesion calculated by back analyses.

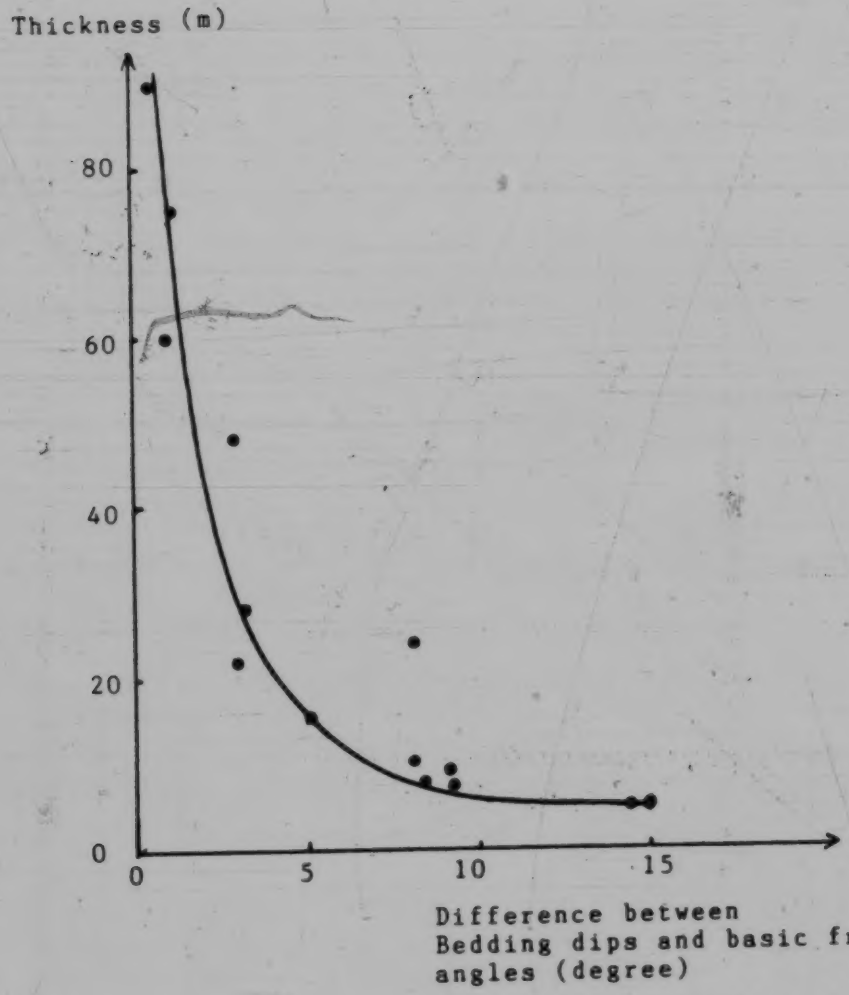
COINT: cohesion calculated from Mohr-Coulomb criterion based on the uniaxial compressive strengths and the basic friction angles from the lab tests.

Figure 6.2 Relationship between lower bounds of cohesion and cohesion of intact rocks

field probably because rock bridges exposed along discontinuities, if any, have been destroyed by weathering. The lower bounds of my back calculations can at least estimate the cohesion of potential sliding planes.

The stable slope profiles of overdip slopes where the dips of penetrative discontinuities do not exceed the basic friction angles can be estimated by rock mass strength ratings (Hu, 1987). If friction and cohesion along bedding surfaces are overcome by sliding forces and slides along bedding surfaces occur, dip slopes result. The stable thickness of a rock slab above a bedding plane decreases with the difference between the bedding dip and the basic friction angles (Fig. 6.3). The curve on Fig. 6.3 is obtained from Equation 1 assuming the cohesion is 40 KPa and the friction angle is 30°. If the friction angle is between 20° and 40° and cohesion is still assumed as 40 KPa, the changes of calculated thicknesses are not appreciable if the difference between the bedding dip and the friction angle is constant. This indicates that the slab thicknesses of potential slides are not sensitive to changes of friction angles but sensitive to changes of cohesion and difference between the bedding dip and the friction angle.

Buckling of beds is also found on some steep dip slopes (chapter 4) and toppling can occur from strike joints.




The curve is derived from the formula by Cruden (1975), assuming the friction angle is 30°. c=40 KPa.

The circles represent the slopes on Fig. 6.2.

Figure 6.3 Relationship between the slab thicknesses of potential rockslides and the differences of bedding dips and basic friction angles

### 6.2.2 Cataclinal underdip slopes

Cruden (1989) showed that toppling can occur on underdip slopes without any assistance. Toppling and buckling are found on these slopes. In the sandstones and laminae of sandstones and shales in the Triassic Spray River Group around the Highwood Pass, the layers can be toppled more than 15 metres deep into rock masses (Chapter 3). The rock layers toppled from dipping SW at 70° to 90° to dipping NE at 0° to 70°. Toppled rock masses may be displaced along sliding surfaces following combinations of bedding surfaces and joints or along sliding surfaces cutting through layers. The slopes of toppled masses are all less than 50° except for those being steepened by undercutting. Toppling processes reduce slope angles and stabilise slopes (chapter 3).

In the Palaeozoic carbonate sequences in Kananaskis Country, only individual blocks on slope surfaces are found toppled when beds are close to vertical. This is probably due to some cohesion along bedding surfaces in carbonates, which stops toppling. While it appears that there is no cohesion along bedding surfaces in the sandstones in the Spray River Group around the Highwood Pass because rock layers are easily separated along bedding planes. The back calculations conducted on overdip slopes show at least some cohesion in some carbonates. Toppling can occur on steep slopes and then blocks loosened by toppling are carried away through sliding or falling on slope surfaces.

Buckling also occurs on steep underdip slopes (chapter 4).

### 6.2.3 Anaclinal slopes

Both sliding and toppling can occur on anaclinal slopes. Movements of the Palaeozoic carbonates and clastics are discussed in Chapter 2. Sliding along strike joints occurs when these strike joints are steeper than 40°. Sliding is found along surfaces oblique to both bedding planes and strike joints when strike joints are about 25° dipping out of slopes and the slope is 60°. The back calculations in Chapter 2 suggest that slope movements can also occur on other steepened anaclinal slopes. Toppling of rock layers from bedding planes may be followed by sliding along the rupture surfaces. Slope surfaces created by sliding along strike joints are parallel to strike joints when their dips are larger than 40° and the slopes are then normal anaclinal slopes. Slope movements take place on steepened anaclinal slopes by toppling followed by sliding or by sliding along combinations of discontinuities. Rock masses can also slide along sheeting joints which are found to develop exclusively in less jointed, strong units on anaclinal slopes.

## 6.3 Slope movements on orthoclinal and plagioclinal slopes

Eaton (1986) identified 67 rockslides or other high magnitude slope movements on orthoclinal and plagioclinal slopes in Kananaskis Country. I visited 19 of these slope movements which have easy access in the summer of 1988 to study mechanisms of slope movements on orthoclinal and plagioclinal slopes. Table 6.1 tabulates the locations, geological formations, bedding orientations and volumes of displaced materials of these slope movements.

Most of the valleys and creeks, particularly large ones, in the study area of Eaton (1986) are trending close to 240° or 150°, perpendicular or parallel to the regional strike of the rocks. There are few valleys or segments of valleys trending at more than 30° to these regional strikes. Plagioclinal slopes are generally at the corners between orthoclinal slopes and anaclinal slopes or cataclinal slopes. Plagioclinal slopes cover a lot less areas than orthoclinal slopes. Slope movements were mainly on orthoclinal slopes or close to orthoclinal slopes.

The slope movements in Table 6.1 are in the Palaeozoic carbonate rocks and clastic rocks in the Peter Lougheed Provincial Park. The angles between the slope directions and the strike of the penetrative discontinuities are all less than 30°.

There are exposed bedding planes on the rockwalls above displaced materials and scars left by the slope movements at all these sites. The shapes of scars depend on discontinuity

Table 6.1 Slope movements on orthoclinal slopes and plagioclinal slopes

| Sites | UTM Locations Easting (m) | Northing (m) | Geological Units | Bedding dips in degree | Volumes of debris ($x10^6 m^3$) |
|---|---|---|---|---|---|
| 1 | 622220 | 5632500 | Mb | 45-50 | 10 |
| 2 | 622150 | 5632250 | Mb | 45-50 | 15 |
| 3 | 621750 | 5631650 | Mr | 45-50 | 10 |
| 4 | 621650 | 5631150 | Mr | 45-50 | 10 |
| 5 | 623100 | 5631200 | Mb | 45-50 | 50 |
| 6 | 622850 | 5630850 | Mr | 45-50 | 30 |
| 7 | 622650 | 5630700 | Mr | 45-50 | 25 |
| 8 | 622300 | 5630350 | Mr | 45-50 | 10 |
| 9 | 624050 | 5630150 | Mb | 35 | 4 |
| 10 | 624000 | 5629950 | Mr | 35 | 20 |
| 11 | 623950 | 5629800 | Mr | 35 | 17 |
| 12 | 623650 | 5628850 | Mr | 38 | 7 |
| 13 | 623450 | 5628600 | Mr | 38 | 7 |
| 14 | 626100 | 5628300 | Mr | 35 | 10 |
| 15 | 626350 | 5628350 | Mr | 35 | 6 |
| 16 | 626250 | 5628200 | Mr | 35 | 8 |
| 17 | 624650 | 5626500 | Mr | 35 | 25 |
| 18 | 624600 | 5626300 | Mr | 35 | 10 |
| 19 | 672900 | 5625700 | Prm | 57 | 75 |

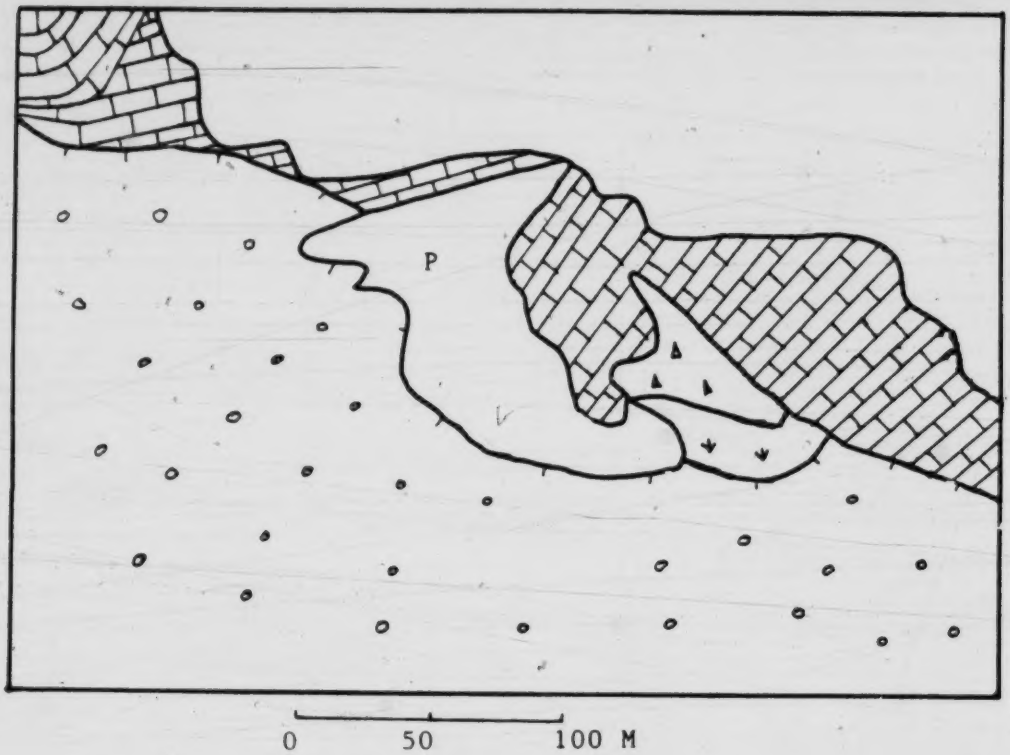
The UTM locations are from the topographic map 82J/14.
Testing results from the portable tilting table

orientations. Rocks with the same discontinuity orientations have the same shape scars. Three examples with different orientations of discontinuities are described to show features of slope movements on orthoclinal and plagioclinal slopes.

### 6.3.1 Site #17

The site is the 17th site on Table 6.1. The site is north of a gully trending NE-SW. There is a clearly seen rupture surface along the bedding plane (Fig. 6.4). The orientation of the bedding plane is 35°/230°. The exposed sliding surface is 76 metres wide and 300 metres long. The sliding surface has some waviness of 5 cm per 10 metres. The rocks are light grey, weathering, medium to thin bedded coarse grained limestones and black to dark gray, thin bedded, fine grained limestones. Strike joints and dip joints at 50°/050° and 90°/140° respectively are dominant joint sets. Another joint set at 68°/095° is infrequent. The bedding thicknesses are 35 cm to 95 cm and the joint spacings are 7 cm to 62 cm.

Part of the sliding surface around the toe of the slope may be daylighted on the ground surface by removal of rock blocks at the toe. Sliding in the direction of the intersection of bedding planes and strike joints assisted by external forces may cause removal of blocks around the toe of the sliding surface (Fig. 6.5). After the sliding surface was daylighted, rock masses slid on the sliding surface and




P: Exposed sliding surface.

Figure 6.4 Slope movements at Site #17

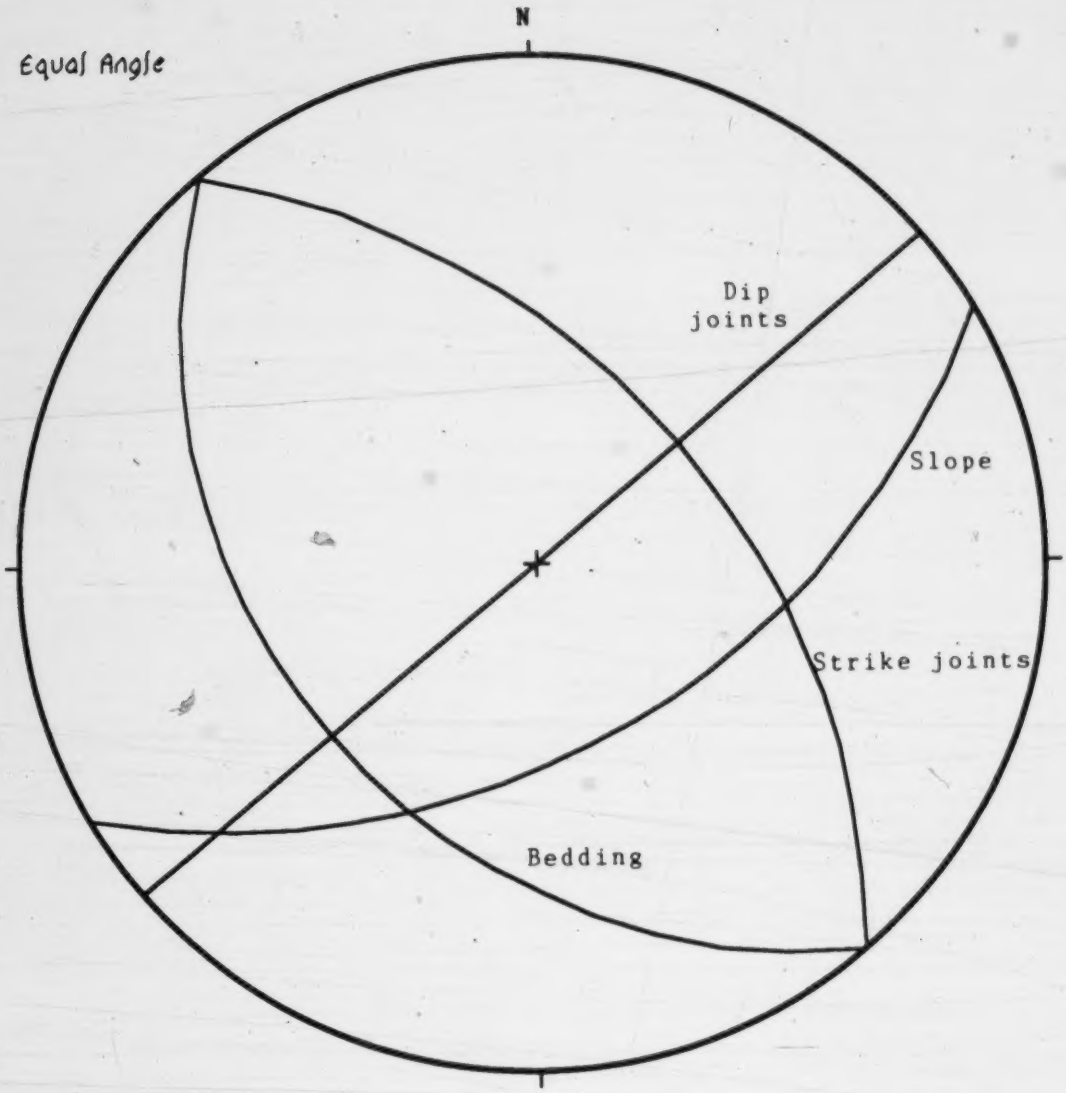


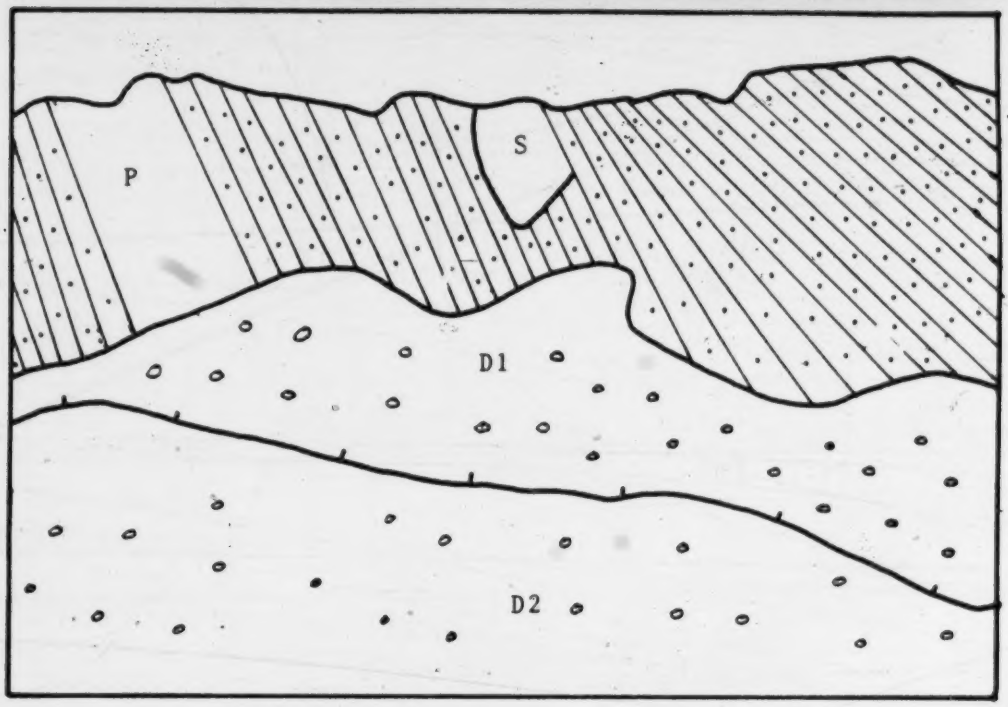

Figure 6.5 Structural diagram at Site #17

then displaced materials were deposited below the bedrock slope. The displaced material is about 25000 $m^3$.

### 6.3.2 Site #19

The site is 2 km east of the Highway #40 and on the south side of the Grizzly Creek and is the 19th site in Table 6.1. The slide occurred in the Permo-Pennsylvania Rocky Mountain Group. The rocks are white to yellowish quartzites. The bedding planes are at 57°/240° and two joint sets are at 30°/060° and 80°-90°/150°. There is a scar left by the displaced materials on the slope (Fig. 6.6). There are exposed bedding planes in the scar. These exposed bedding planes are estimated as 30 m to 50 m wide and extend from the toe to the crest of the slope.

There was more than one movement event. The displaced materials close to the rock slope look younger than those far from the rock slope. There are some potential sliding blocks on the bedding surface in the scar. The scar in the rock slope may be a glacial cirque or simply formed by sliding. Then the potential sliding rock masses left in the scar slid along the bedding surfaces and deposited below the rock slopes forming the younger deposits. The slope movements may also be caused by toppling about the intersection of the bedding plane and the strike joints. The rock masses toppled out of the slope surface from dip joints (Fig. 6.7). Water and ice may assist toppling by entering dip joints. The volume of the total displaced materials is




0 ——— 50 M

P: exposed rupture surface along bedding planes.
S: potential sliding rock masses.
D1: young displaced materials.
D2: old displaced materials.

Figure 6.6 Slope movements at Site #19

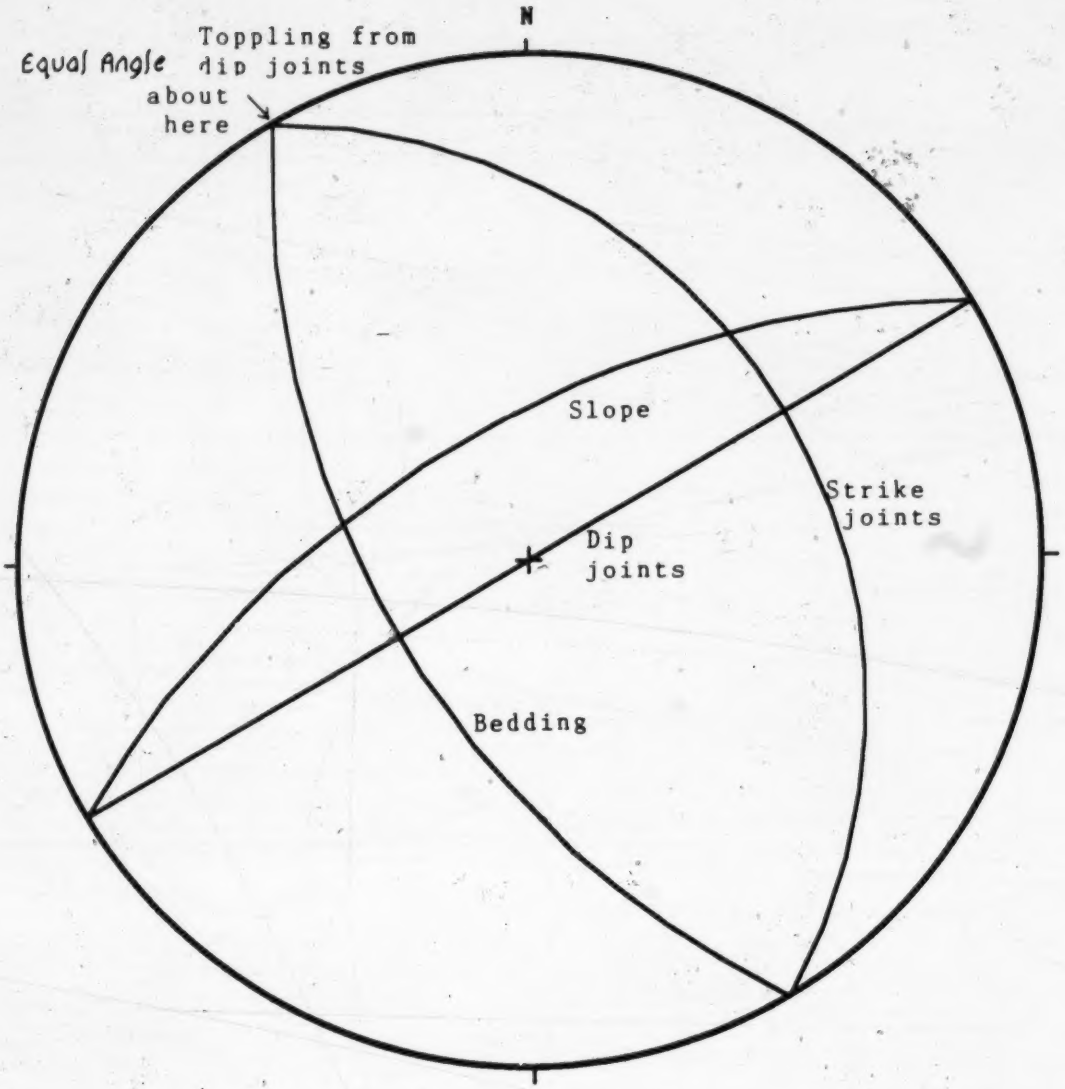



Figure 6.7 Structural diagram at Site #19

about 75000 $m^3$.

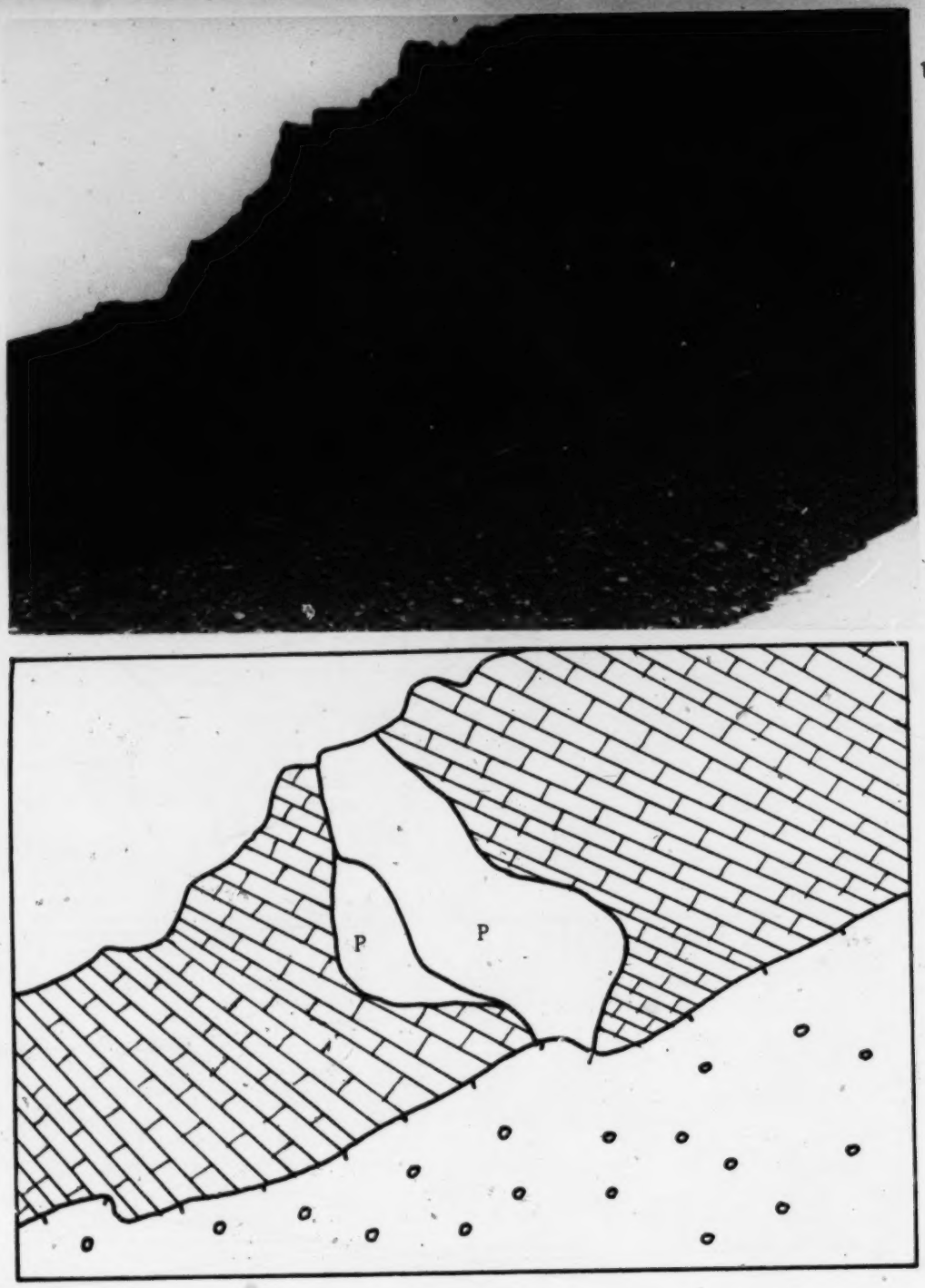
### 6.3.3 Sites #9-#11

The sites are located in the Headwall Creek and 5 km from the Smith-Dorrien-Spray Trail. There are three deposits displaced from different bedding planes on the rockwall on the south side of the gully. The rocks are black to dark gray, fine grained limestones in the Mississippian Rundle Group. There are also some chert layers. The bedding planes are at 38°/220°. The strike joints and dip joints (80°-90°/130° and 50°/045°) are dominant. Other joint sets at 65°/280° are also found but poorly developed.

There is an exposed bedding plane above each deposit (Fig. 6.8) and these bedding planes are about 20 m wide and extend from the toe to the crest of the slope, which suggests that the deposits were displaced along the bedding planes. The volumes of the displaced materials are between 4000 $m^3$ and 20000 $m^3$.

The slope surface is rugged due to erosion, which may cause daylighting of some bedding planes. Blocks around the toe of the sliding planes were removed by sliding of rocks in the direction of intersection of bedding planes and strike joints (Fig. 6.9). Then rock masses slid down the sliding plane and the displaced materials were deposited below the slope.

In summary, since there are exposed bedding planes on rockwalls on orthoclinal and plagioclinal slopes and the




P: Exposed rupture surfaces along bedding planes.

Figure 6.8 One of the exposed sliding surfaces at Sites #9-#11 and some debris

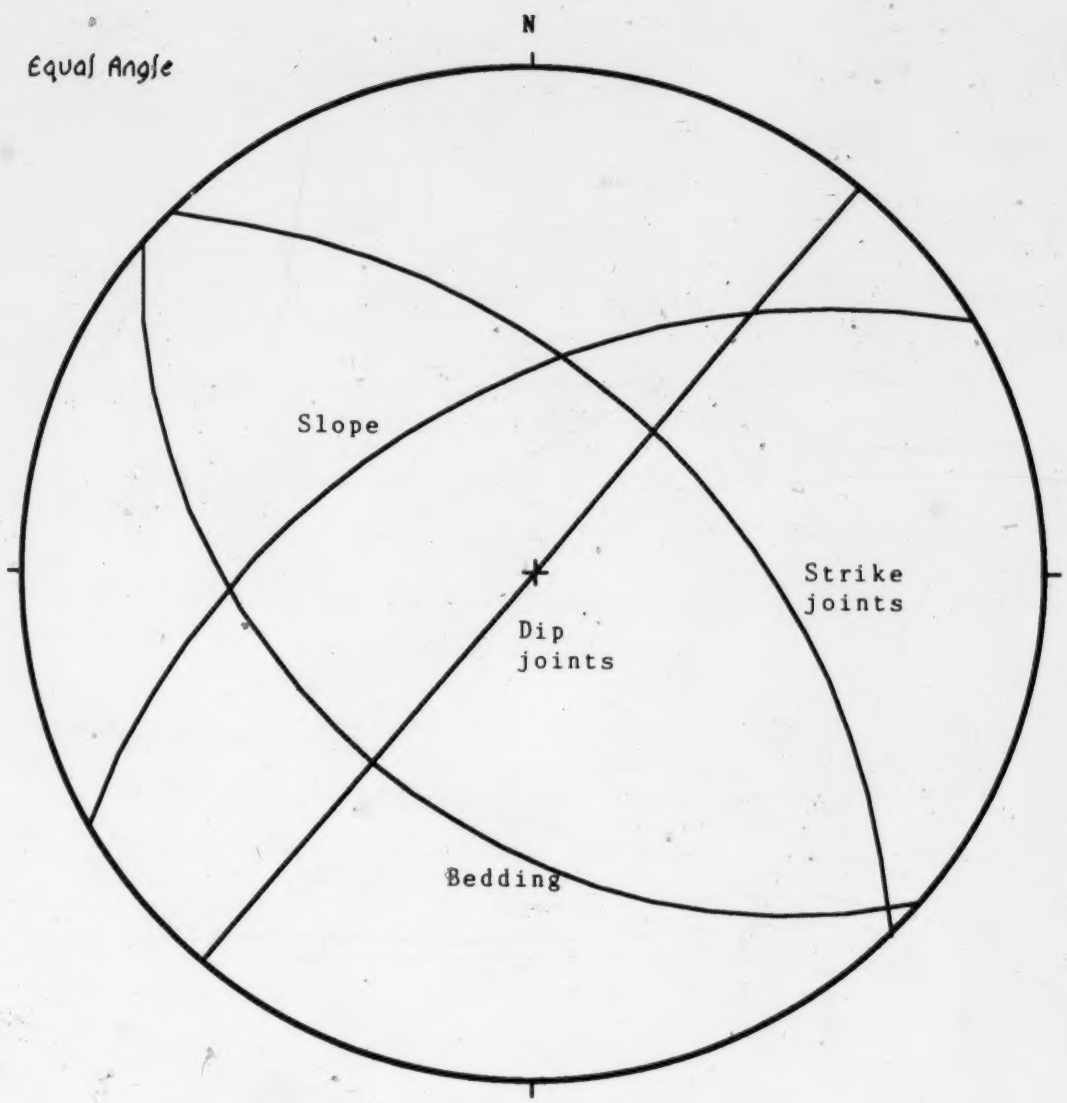



Figure 6.9 Structural diagram at Sites #9-#11

rupture surfaces left by displaced rock masses, these rock masses have been displaced along exposed bedding surfaces. There are no penetrative discontinuities dipping out of the slopes. Slides along bedding surfaces are possible when rock masses around the toes of sliding planes are removed. Sliding of rock blocks may occur in the direction of the intersection of bedding planes and strike joints. Sliding is assisted by external forces. These slides can cause daylighting of some bedding surfaces around toes of slopes.

Toppling about intersections of bedding planes and strike joints may also occur. Toppling blocks are separated from dip joints and rotate out of slopes. Water and ice may assist toppling by entering dip joints.

After sliding of blocks around the toes of slopes along the intersections of bedding planes and strike joints, bedding planes daylight around the toes of slopes, rock masses slide down sliding planes and deposit below the slopes. Due to lateral restraint, the volumes of displaced materials are small compared to slides such as those on cataclinal overdip slopes.

Since movements of displaced rock masses along bedding planes are almost parallel to slopes, displaced materials are not deposited far from the rock slopes compared with slope movements on overdip slopes. All the movements in Table 6.1 occurred where bedding dips are steeper than 30°. When beds are flat lying, rock masses may be displaced by small falls and topples.

## 6.4 Slope movement processes

When rock masses are displaced, catastrophic mass movements generally involve large volumes of rocks sliding along some surfaces, sometimes follow other types of movements. Noncatastrophic movements involve small volumes of rocks and can be repeated many times over a long time but the mode of movements can be changed too. For example, toppling of rock layers may become sliding of rock masses along rupture surfaces. The process diagram of Cruden (1987) only gives modes of movements on different slopes when slope movements start. Table 6.2 gives a summary of different modes of slope movements at different stages on different slopes based on my studies in the previous chapters. Landforms formed by slope movements are the results of the second stage of movements and rock masses are displaced either from bedrock rockwalls or through rock basins by sliding or falling.

## 6.5 Slope movements and landforms

Catastrophic slope movements and noncatastrophic slope movements together modify slopes originally created by the erosion of the last glaciation. Catastrophic slope movements seldom form rock basins. Mass movements in the 55 open rock basins I investigated are all noncatastrophic movements except in one basin on anaclinal slopes, where $6 \times 10^4$ $m^3$ of rock masses was displaced as one-time event and the slope movement, Elk Ridge slide is studied in Chapter 2.

Table 6.2 Slope movements at different stages

| Slope types | Primary Movements | Secondary Movements |
|---|---|---|
| Overdip slopes | Sliding along bedding<br>Toppling from joints | Sliding along bedding<br>Falling |
| Dip slopes | Buckling of bedding | Sliding along rupture surfaces |
| Underdip slopes | Toppling from bedding | Sliding along rupture surfaces<br>Falling |
| Orthoclinal slopes | Sliding along bedding<br>Toppling from dip joints. | Sliding along bedding<br>Falling |
| Anaclinal slopes | Sliding along strike joints, along sheeting joints or along combinations of discontinuities.<br>Toppling from bedding. | Sliding along strike joints, along sheeting joints or along combinations of discontinuities. |

Noncatastrophic mass movements displace rock masses either in rock basins where rock blocks are separated from bedrock slopes then carried away or on slopes where rock blocks topple or slide then fall or slide. Noncatastophic movements involve small volumes of rock masses at a time but movements repeat over a long time. As with slope movements not in open rock basins, gradients of slopes in open rock basins are related to geological structures.

Fig 6.10 gives the relationship between slope angles and bedding dips of the basins on different types of slopes. Because some of the basins are large in size and close to thrust faults, there are big ranges of dips of beds in these basins. Table 6.3 gives the bedding orientations and the slope angles of 55 rock basins. Dip directions and dips of bedding planes were measured with a Brunton pocket transit at accessible locations in the basins. Up to ten measurements were taken at each location and averaged to give the mean values of bedding orientation. Dip values within a basin may have a range of up to fifty degrees due to local folding of the bedding. Slope angles were taken on the parts of bedrock slopes in the directions of the long axes of the basins.

There are generally no large volumes of rock masses displaced at one time in most of the open rock basins. This would imply that most of the rock basins are stable with respect to catastrophic slope movements because of the movement types and characteristics determined by the

Table 6.3. Bedding orientations and slope angles of 55 open rock basins.

| | Basins | Bedding Orientations (degree) | Slope Angles (degree) | Geological Units |
|---|---|---|---|---|
| Orthoclinal Slopes | 1 | 40-50/240 | 47 | Prm |
| | 2 | 40-50/240 | 40 | Prm |
| | 3 | 40-50/240 | 38 | Prm |
| | 4 | 80/240 | 43 | Mr |
| | 5 | 80/240 | 31 | Mr |
| | 6 | 85-90/240 | 45 | Mr |
| | 7 | 85-90/240 | 45 | Mr |
| | 8 | 90/240 | 36 | Mr |
| Cataclinal Overdip Slopes | 9 | 35/240 | 39 | Mr |
| | 10 | 35/240 | 38 | Mr |
| | 11 | 35/240 | 39 | Mr |
| | 12 | 35/240 | 37 | Mr |
| | 13 | 35/240 | 36 | Mr |
| | 14 | 25/215 | 37 | Mr-Prm |
| | 15 | 60/249 | 60 | Dp-Me |
| Anaclinal Slopes | 16 | 0-50/240 | 60 | Mb-Mr |
| | 17 | 30-40/220 | 54 | Mr |
| | 18 | 30-60/240 | 45 | Dp-Me-Mb-Mr |
| | 19 | 30-60/240 | 45 | Dp-Me-Mb-Mr |
| | 20 | 25-30/200 | 47 | Mr |
| | 21 | 30/240 | 41 | Mr |
| | 22 | 40-60/240 | 60 | Mr |
| | 23 | 70-90/240 | 75 | Dp |
| | 24 | 65-90/240 | 75 | Dp |
| | 25 | 60-65/240 | 65 | Dp-Me-Mb-Mr |
| | 26 | 60-65/240 | 70 | Dp-Me-Mb-Mr |
| | 27 | 60-65/240 | 70 | Dp-Me-Mb-Mr |
| | 28 | 90/240 | 60 | Mr |
| | 29 | 88-90/240 | 55 | Mr |
| | 30 | 88/243 | 54 | Mr |
| | 31 | 63-70/240 | 47 | Mr |
| | 32 | 63-70/240 | 41 | Mr |
| | 33 | 63-70/240 | 47 | Mr |
| | 34 | 63-70/240 | 49 | Mr |
| | 35 | 63-70/240 | 45 | Mr |

Continued on the next page...

Table 6.3. Continued from the previous page...

| | Basins | Bedding Orientations (degree) | Slope Angles (degree) | Geological Units |
|---|---|---|---|---|
| | 36 | 80-90/240 | 38 | Mr |
| | 37 | 70-90/240 | 41 | Mr |
| | 38 | 70-90/240 | 42 | Mr |
| | 39 | 60-90/240 | 40 | Mr |
| | 40 | 60-90/240 | 39 | Mr |
| | 41 | 60-70/240 | 42 | Prm |
| | 42 | 60-70/240 | 39 | Prm |
| Cataclinal | 43 | 60-70/240 | 41 | Prm |
| Underdip | 44 | 85-90/250 | 37 | Mr |
| Slopes | 45 | 85-90/250 | 43 | Mr |
| | 46 | 75-80/240 | 43 | Mr-Prm |
| | 47 | 75-80/240 | 45 | Mr-Prm |
| | 48 | 75-80/240 | 45 | Mr-Prm |
| | 49 | 75-80/240 | 48 | Mr-Prm |
| | 50 | 75-80/240 | 47 | Mr-Prm |
| | 51 | 75-80/240 | 50 | Mr-Prm |
| | 52 | 75-80/240 | 50 | Mr-Prm |
| | 53 | 75-80/240 | 41 | Mr-Prm |
| | 54 | 75-80/240 | 43 | Mr-Prm |
| | 55 | 75-80/240 | 36 | Mr-Prm |

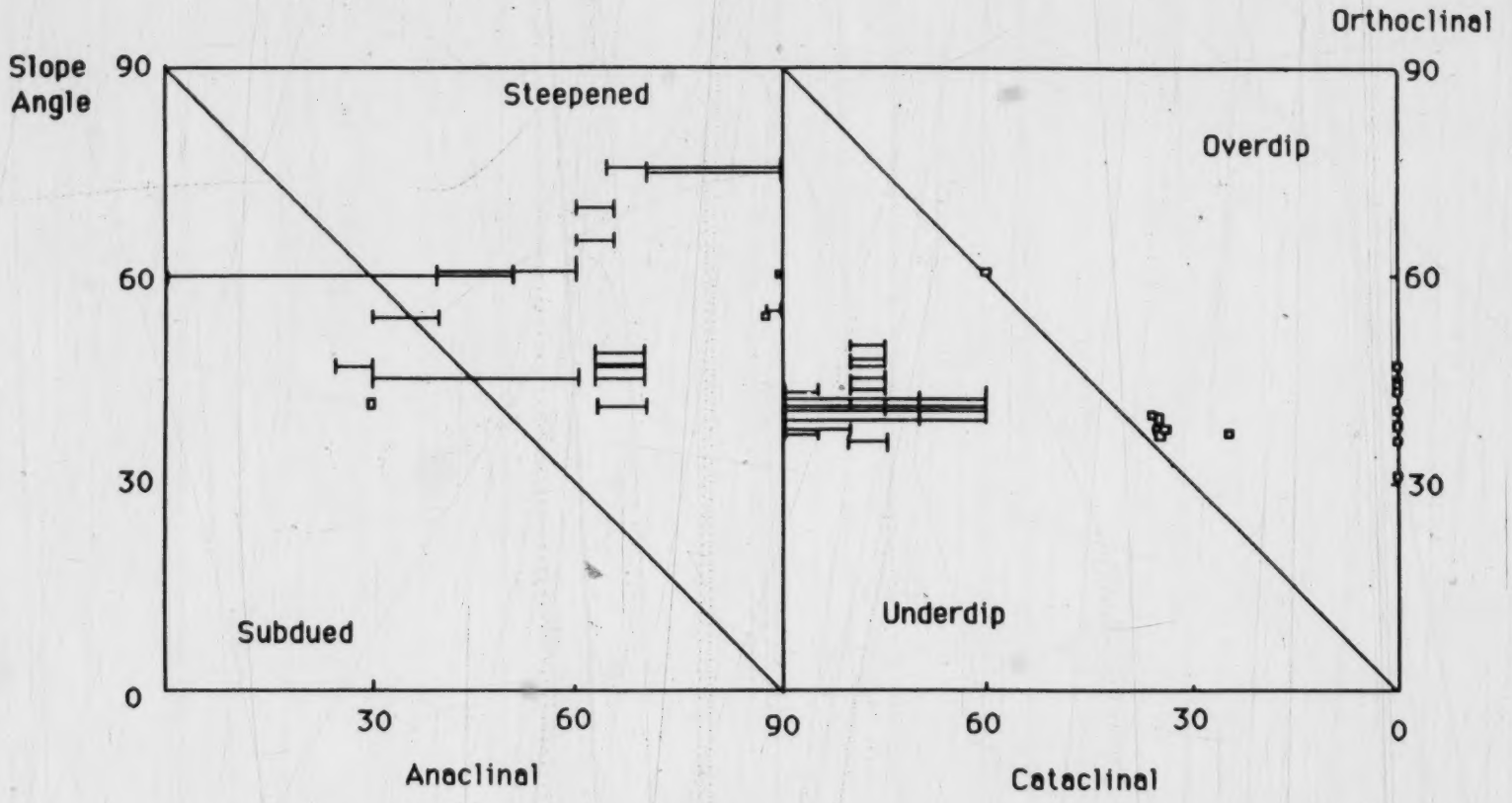



Fig. 6.10. Relationship between bedding dips and slope angles for 55 open rock basins.

geological structures. The displacements of rock masses in most open rock basins are gradual and transport rock materials from bedrock slopes to talus slopes. The resultant landforms in an open rock basin may differ from those formed by movements not in basins.

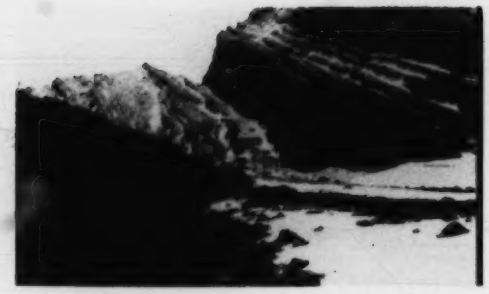
There are no rock basins when slope angles are less than 30° (Fig. 6.10) and there are no bedrock slopes gentler than 30° either. Talus slopes dominate when slopes are gentler than 30°.

### 6.5.1 Orthoclinal slopes

Eight basins on orthoclinal or plagioclinal slopes have slope angles ranging between 40° and 56°. These basins are long and narrow (Sauchyn et al., 1990) (Fig. 6.11 A) and develop along relatively weak layers in the rock sequences. Rock blocks in weaker layers topple from dip joints when beds are steep or/and slide along bedding planes then are displaced in these basins. The variations of slope angles in the basins are probably dependent on stages of development of slope profiles. Catastrophic mass movements can also occur on this type of slope and basins may be wider if large volumes of materials are displaced by sliding (e.g. Fig. 6.6).

### 6.5.2 Dip and overdip slopes

On dip and overdip slopes, slope movements are slides along bedding planes or topples from strike joints. When



(A). Basin 1

(B). Basin 15.

(C). Basin 14

(D). Basin 44.

(E). A basin from Mount Shark.

Figure 6.11. Features of open rock basins.

bedding dips exceed basic friction angles of the rocks, rock masses on bedding surfaces have slid and dip slopes remain. When bedding dips do not exceed basic friction angles of the rocks or there is some cohesion on bedding planes even when bedding dips exceed basic friction angles a little, overdip slopes remain. Thicknesses of rock slabs above potential sliding planes are determined by cohesion and differences between bedding dips and friction angles. When the bedding dip is less than the basic friction angle, rock masses move by toppling from strike joints and the slope angle is correlated with the rock mass strength rating (Hu, 1987).

Comparing Fig. 6.10 with the process diagram of Cruden (1987, Fig.5), there are few basins in the region of overdip slopes not close to dip slopes where slope movements are sliding on bedding and/or toppling from kathetal joints. Dominant slope movements on these overdip slopes, catastrophic rockslides such as the slide in Mount Indefatigable (Eaton, 1986) occur to form dip slopes.

On Fig. 6.10, open rock basins develop where bedding dips are steeper than 40° on dip slopes (Fig. 6.11 B) or where bedding dips are less than 40° on overdip slopes (Fig. 6.11 C). Mass movements from rock basins on dip slopes may be removal of some blocks from toes of rockwalls followed by sliding of daylighted rock masses or toppling of blocks from bedding planes. Mass movements from basins on overdip slopes are toppling from strike joints or assisted sliding along bedding planes of individual blocks then loosed blocks slide

on slope surfaces or fall.

### 6.5.3 Cataclinal underdip slopes

On underdip slopes, slope angles of the rock basins are between 36° and 50° and the bedding dips are 70° to 90°. Slope angles are not dependent on bedding dips (Fig. 6.10). The basins are all in the Paleozoic carbonates and clastics (Table 6.3). In contrast to processes in the Mesozoic sandstones, the individual blocks are separated from bedding planes by toppling probably with external assistance and then carried away by sliding on basin slopes to form the basins (Fig. 6.11 D). These underdip slopes were created by glacial erosion and the processes of toppling and carrying away of rock blocks gradually reduce slope gradients until slope angles reach values at which toppling stops.

Toppling in the steeply dipping Mesozoic sandstones involves thick rock masses. Rotations of layers finally stabilize slope surfaces or sliding follows toppling in toppled rock masses on local ridges dissected by gullies. Slope angles of toppled rock masses are related to original slopes, rock structures or orientations of toppled layers (Chapter 3).

There are no basins developed on slightly underdip slopes , which may indicate that mass movements causing the formation of rock basins are not active on slightly underdip slopes in the Palaezoic carbonates and clastics. Cruden (1991) showed that on these slopes, toppling of blocks from

bedding planes with sliding of blocks along bedding planes and kathetal joints is not kinematically possible. Toppling of blocks with sliding only along bedding planes needs more energy from external sources. Also because open rock basins generally have concave profiles, removal of blocks from the feet of rock walls leads to the formation of dip slopes after subsequent sliding caused by the removal. Removal of blocks does not form concave rock basins.

### 6.5.4 Anaclinal slopes

On anaclinal slopes, when bedding dips are between 30° and 40° into slopes, slopes of the basins are close to those of normal anaclinal slopes (Cruden and Hu, 1990) and slopes are more or less parallel to strike joints. As with slope movements on normal anaclinal slopes (Chapter 2) not in rock basins, slope movements on normal anaclinal slopes in rock basins are slides along strike joints.

The basins on steepened anaclinal slopes have bedding dips larger than 40° (Fig. 6.10), which indicate that slopes are overdip slopes with respect to strike joints (Fig. 6.11 E). Steepened anaclinal slopes were created by glacial erosion. These slopes may move later by toppling followed by sliding along rupture surfaces or sliding along combinations of strike joints and bedding planes to reduce slope angles (Chapter 2). The noncatastrophic processes are toppling of rock blocks and falling or sliding of these blocks, which may reduce slope gradients of steepened anaclinal slopes

gradually if catastrophic movements do not occur.

There are some subdued anaclinal slopes in the basins (Fig. 6.10) and they are underdip slopes with respect to strike joints. Toppling from strike joints is the mode of movements on these slopes according to the process diagram of Cruden (1987). Individual blocks are toppled from strike joints and carried away on slope surfaces and then slope angles are reduced.

Some of the slopes in the basins have wide ranges of bedding dips and Fig. 6.10 only give average slope angles in the long axes of the basins, the slopes in the basins extend from subdued to normal to steepened slopes in different parts of the slopes. In fact, either the lower part or the upper part can be subject to sliding along strike joints depending on bedding dips on different parts. The processes may be more complex. For example, sliding rock masses on the upper part of slopes can push rock masses on the lower part where rock masses are not subject to sliding.

On anaclinal slopes, stability of slopes with respect to catastrophic movements is controlled by many factors such as block structures, friction properties of rocks, topography of slopes and probably cohesion, not only by orientations of discontinuities and slope angles. So rock basins develop on anaclinal slopes in a large region in Fig. 6.10, not only dependent on slope angles and bedding dips.

## 6.6 Conclusions

Slope movements in stratified rocks are determined by orientations of discontinuities. Different modes of slope movements on different slope types control evolution of slopes. Rock masses are displaced either from rock slopes by sliding or falling or in rock basins.

On dip and overdip slopes, sliding along bedding planes produce slopes parallel to bedding planes. Overdip slopes result when sliding forces along potential sliding planes do not exceed sliding resistance. The thickness of a potential sliding slab is determined by the cohesion and the difference between the bedding dip and friction angle. Rock mass strength ratings are correlated with slope angles when bedding dips are less than friction angles. In rock basins on overdip slopes where bedding dips are less than 40°, rock blocks are toppled from strike joints and then slide on slope surfaces or fall. In rock basins on dip slopes, rock masses may be removed first around the feet of slopes followed by sliding along bedding planes or rock blocks topple from bedding planes. There are no basins on overdip slopes with steep bedding planes.

On orthoclinal slopes, toppling from dip joints and sliding along bedding surfaces are modes of slope movements. These slope movements may develop along some weak units. Rock basins form as the results of toppling or sliding.

On anaclinal slopes, sliding along strike joints produce normal anaclinal slopes. Steepened anaclinal slopes

may be subject to catastrophic movements by toppling followed by sliding or by sliding along combinations of discontinuities or when individual rock blocks are toppled and moved away by falling. On subdued anaclinal slopes, toppling occurs from strike joints. Rock basins form and develop through these slope movements on anaclinal slopes. Basins develop on wide ranges of bedding dips and slope angles because not only topography and bedding dips but also block structures, cohesion and friction all influence slope movements in the basins.

On cataclinal underdip slopes, individual blocks are toppled and carried away through rock basins in the steep dipping Paleozoic carbonates and clastics to reduce slope angles. Rock basins do not develop on slightly underdip slopes for kinematic reasons. In the Mesozoic sandstones, beds are toppled on ridges dissected by gullies and toppling processes are influenced by slope angles and block structures (Chapter 3). Toppling, sometimes followed by sliding reduces slope angles and slopes develop towards stable characteristic forms.

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## 7. Opportunities for further work and conclusions

In this chapter, I first review the opportunities for further work that have arisen from my research. Then I summarize the conclusions, first generally, then in detail.

### 7.1 Opportunities for further work

The thesis research has studied slope movements in all the different types of slopes in stratified rocks in Kananaskis Country. But most of the results are still semi-quantitative. There is still a lot to be done with many aspects of evaluating slope stability and predicting slope movements more accurately.

On anaclinal slopes, either toppling or sliding may occur with certain orientations of discontinuities and slopes according to the process diagram by Cruden (1987). Aydan *et al.* (1989) illustrated failures of rock block structures with different discontinuity orientations, spacings and arrangements by physical models. The failures of their models have different rupture surfaces and different modes for different block structures and different slopes. Modes include sliding along throughgoing discontinuities, sliding along rupture surfaces followed by toppling or toppling only. For highly jointed rocks on anaclinal slopes in stratified rocks such as the rocks in the Mount Head Formation, different rupture surfaces and different modes of movements may also develop depending on different rock block structures and slope angles. Volumes

and sliding surfaces are probably uniquely determined by geological structures and topography on anaclinal slopes. The models used in Chapter 2 cannot predict these volumes or sliding surfaces and more advanced models may provide better solutions. Cohesion along penetrative discontinuities and along joints can influences slope stabilities.

Topples on cataclinal underdip slopes in the Mesozoic sandstones experience large rotations which change the dip directions of layers and form anaclinal slopes. Processes of toppling are determined by rock block structures and topography (Chapter 3). My research reports the features of the topples and describes toppling processes. Displacements of rock blocks at different stages of toppling and stabilities of slopes of toppled layers at different orientations have not been studied in detail. The formation of sliding surfaces needs to be explained further.

Only individual blocks toppled in the Palaeozoic carbonate sequences and there are no topples on slightly underdip slopes. Friction properties and cohesion along discontinuities and/or block structures in these sequences must be different from those in the Mesozoic sandstones which appear cohesionless. The quantitative relationship among slope angles, orientations of discontinuities, block structures, toppling styles and maximum depths of toppling into rock masses still needs to be studied.

For buckles and topples on steep cataclinal dip slopes and underdip slopes, the effects of pore pressures and

freezing have not been explained but only briefly mentioned. These effects are important for buckling without high rockwalls. Strengths of rock blocks and rock masses are one of the important factors for buckling. To evaluate buckling processes, including further movements after initial buckling, quantitatively, effects of rock mass strength and stiffness should be taken into consideration.

## 7.2 Conclusions

### 7.2.1 General conclusions

Some general conclusions can be drawn from this analysis of rock slopes in Kananaskis Country.

Rock slope movements in Kananaskis Country can be explained assuming that the slopes are formed from rigid blocks with little cohesion, margined by natural discontinuities. Most movements are drained. The style of the folding movements, toppling and buckling, is determined by bedding thickness and ratio of joint spacing to bedding thickness. Catastrophic buckles and topples have occurred on underdip slopes and steepened anaclinal slopes.

Open rock basins remain on slopes that have not moved. The absence of cohesion on bedding planes has prevented the formation of open basins on steep, dip and slightly underdip slopes. Anaclinal slopes with open rock basins plotting above the thresholds for catastrophic movements exist probably due to cohesion on kathetal joint systems.

Friction angles on bedding planes are adequately estimated by the basic friction angles and can be measured on tilting tables.

### 7.2.2 Detailed conclusions

Detailed conclusions can be summarized by the type of slope.

On anaclinal slopes, either sliding along kathetal joints or toppling from bedding planes can occur. When bedding dips are less than 50° or strike joints are steeper than 40°, rock masses slide along strike joints on normal anaclinal slopes. When bedding layers dip at about 65° into slopes on steepened anaclinal slopes, large slope movements may occur. Rock masses topple from bedding planes followed by sliding along rupture surfaces or slide along sheeting joints to reduce slope gradients.

Kathetal joints are generally not throughgoing discontinuities, so long rock columns formed by kathetal joints do not exist to form buckles as in the process diagram of Cruden (1987).

On cataclinal underdip slopes, topples progress from the ground surface into rock masses in Mesozoic sandstones. Depending on different block sizes and ratios, topples can be block flexure topples, chevron topples and complex multiple block topples. Block flexure topples develop where h/b is 1 to 2. Complex multiple block topples develop where h/b is 2 to 20 and sliding surfaces and steep cracks can

form in toppled rock masses during the toppling processes. Chevron topples develop on slopes steeper than 35° where h/b is 2 to 20. Sliding can occur along hinge surfaces and steep cracks can also form in chevron topples. Toppling generally reduces slope angles and stabilises slopes. Toppling ends when the slopes are stable.

On steep dip slopes and underdip slopes, buckles of rock layers occur and buckling styles are dependent on bedding thicknesses and joint spacings. In thickly bedded layers, Euler buckles, block flexure buckles and block buckles develop. There are no kathetal joints in Euler buckles. Rock blocks separated by kathetal joints gradually change orientations along buckled layers in block flexure buckles. Buckled rock blocks rotate large angles in block buckles. Chevron buckles develop in thin to medium bedded layers. More than one layer can be involved in buckling. Further movements of buckles can lead to cascades and roof and wall structures. Failures of buckles deposit large volumes of displaced materials.

On cataclinal overdip slopes, sliding occurs when fricton and cohesion are overcome by sliding forces. Dip slopes are left after rockslides. When sliding forces can not overcome cohesion but dips of potential sliding planes are larger than the friction angles of potential sliding planes, slabs of rock layers form overdip slopes. When bedding dips are less than friction angles, sliding can not occur only by gravity. Rock masses may move by toppling from

kathetal joints or by assisted sliding.

On orthoclinal and plagioclinal slopes, slope movements are either sliding of toe blocks of potential sliding planes along intersections of bedding planes and strike joints followed by sliding down bedding planes or toppling from dip joints with external assistances.

The portable tilting table is useful equipment for tilting tests in the field. As many smooth discontinuity surfaces as desired can be tested. The minimum sliding angle from smooth surfaces can be used as an estimate of the basic friction angle of discontinuities in sandstones. Siltstones and shales can also be tested in the field when they may not survive transportation.

Besides the large slope movements studied on different types of slopes, smaller rock masses have also been displaced to form open rock basins. The processes of modifying slopes to form open rock basins are also determined by rock mass structures. In particular,

1. On slopes less than 30°, talus generally covers slopes.
2. On overdip slopes, rock basins can form when bedding dips are less than 40°.
3. Rock basins occur on cataclinal underdip slopes in the Palaeozoic carbonates and clastics. Individual rock blocks are toppled then carried away in the basins and this process reduces slope gradient until toppling ends. Basins do not develop on slightly underdip slopes.
4. On anaclinal slopes, basins occur in wide ranges of

slope angles and bedding dips. Rock masses are displaced either by sliding along strike joints on normal anaclinal slopes, by toppling from bedding planes followed by sliding along rupture surfaces on steepened anaclinal slopes or by toppling from strike joints followed by sliding or falling on subdued anaclinal slopes. Catastrophic movements can create rock basins on steepened anaclinal slopes.

5. On orthoclinal slopes, rock basins form by toppling of rock masses from dip joints or by sliding along the intersection of bedding planes and strike joints. Removal of rock blocks around the toes of slopes are followed by sliding down the dips of bedding planes. Topples of blocks generally occur in relatively weak units.

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